CCD Development at LBNL

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SNAP Synergy

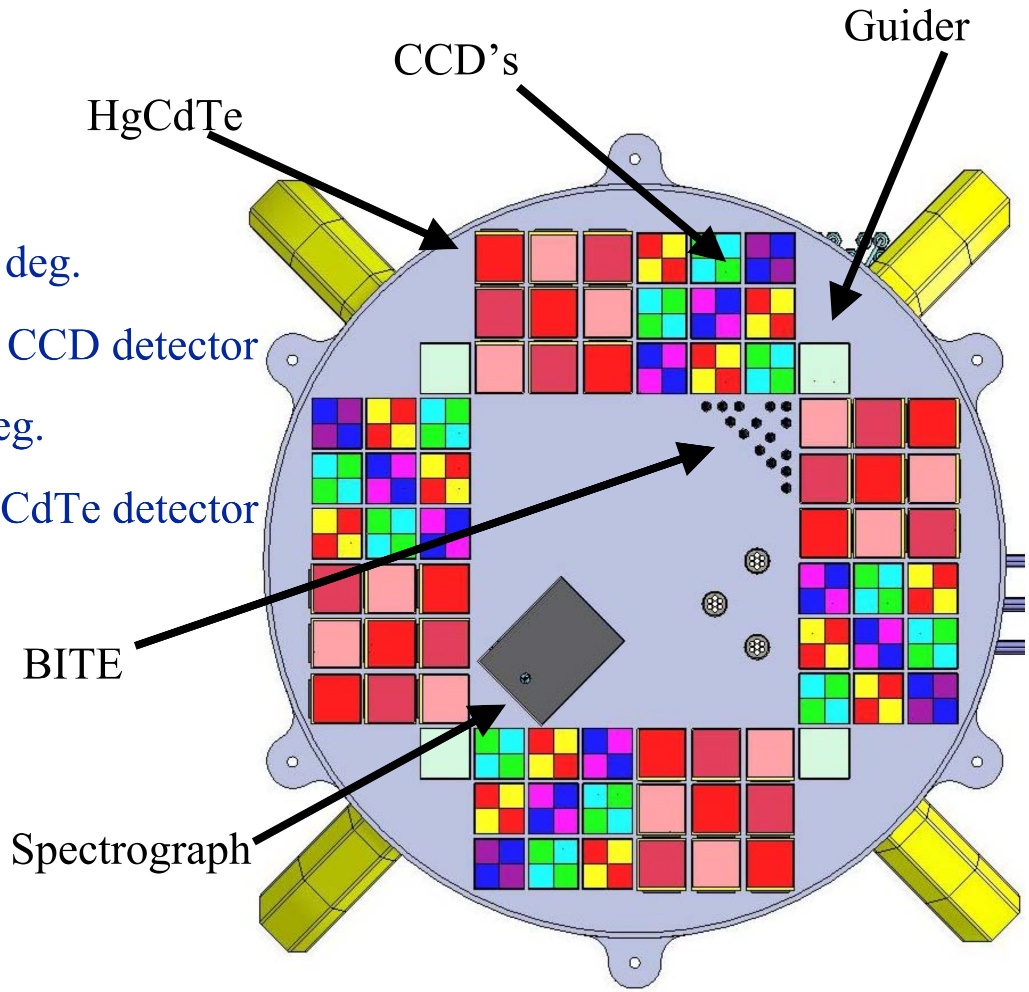
- **SNAP camera: half-billion pixel mosaic camera, high-resistivity, rad-tolerant p-type CCDs (0.35-1.0 μm) and, HgCdTe arrays (0.9-1.7 μm).**

Field of View Optical (36 CCD's) = 0.34 sq. deg.

Four filters on each 10.5 μm pixel CCD detector

Field of View IR (36 HgCdTe's) = 0.34 sq. deg.

One filter on each 18 μm pixel HgCdTe detector



LBNL CCDs

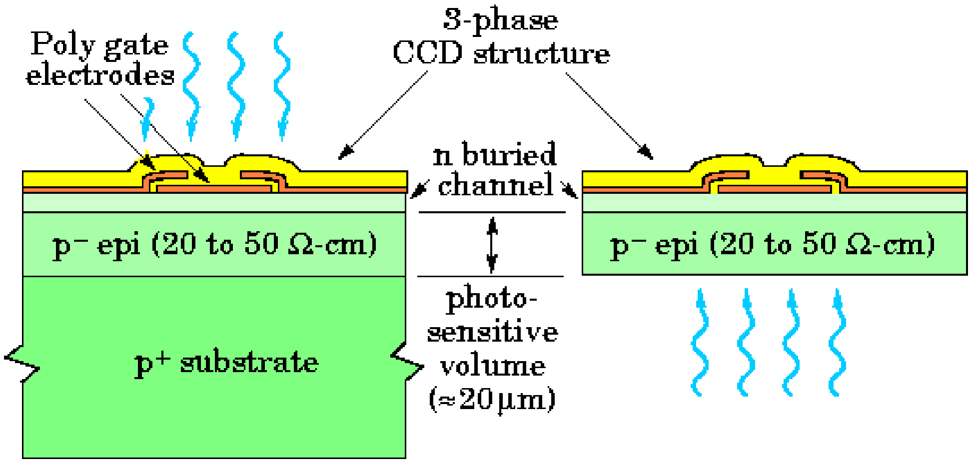
- LBNL Development started in early 1990's:
  - —Fully depleted CCD's fabricated on high-resistivity silicon developed for SSC HEP applications
  - —p-channel CCD has improved radiation tolerance
  - —Now being developed for astronomical applications, e.g. SNAP – higher QE over broader wavelength range than previous astronomical grade CCD's, no fringing

- Patents Issued
  - — ***U.S. Patent 6,259,085 "Fully Depleted Back Illuminated CCD", Jul. 10, 2001.***
  - — ***U.S. Patent 6,025,585 "Low-resistivity photon-transparent window attached to photosensitive silicon detector", Feb. 15, 2000.***

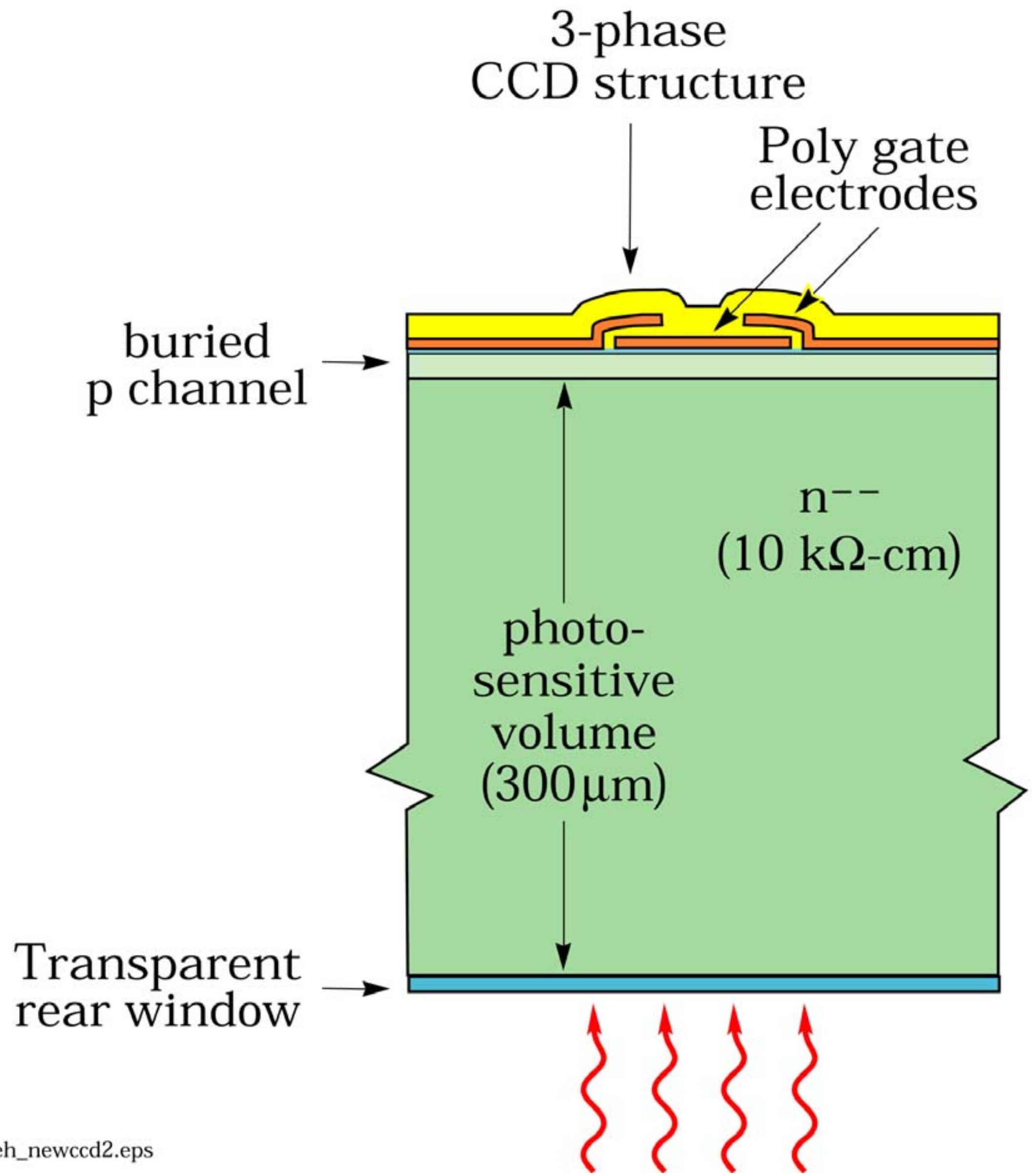
Scientific CCDs

Front-illuminated n-channel on p-type, low-resistivity silicon

Thinned, back-illuminated n-channel on p-type, low-resistivity silicon

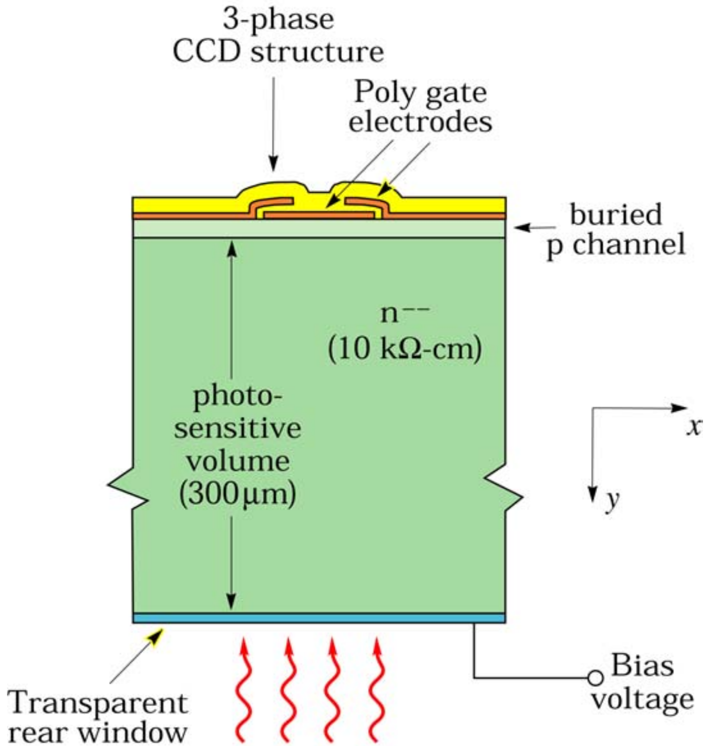


CCD Technology

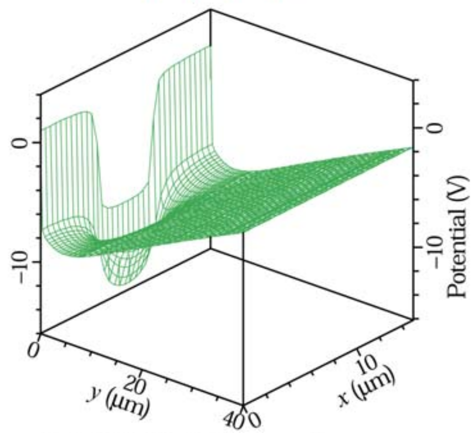


seh_newccd2.eps

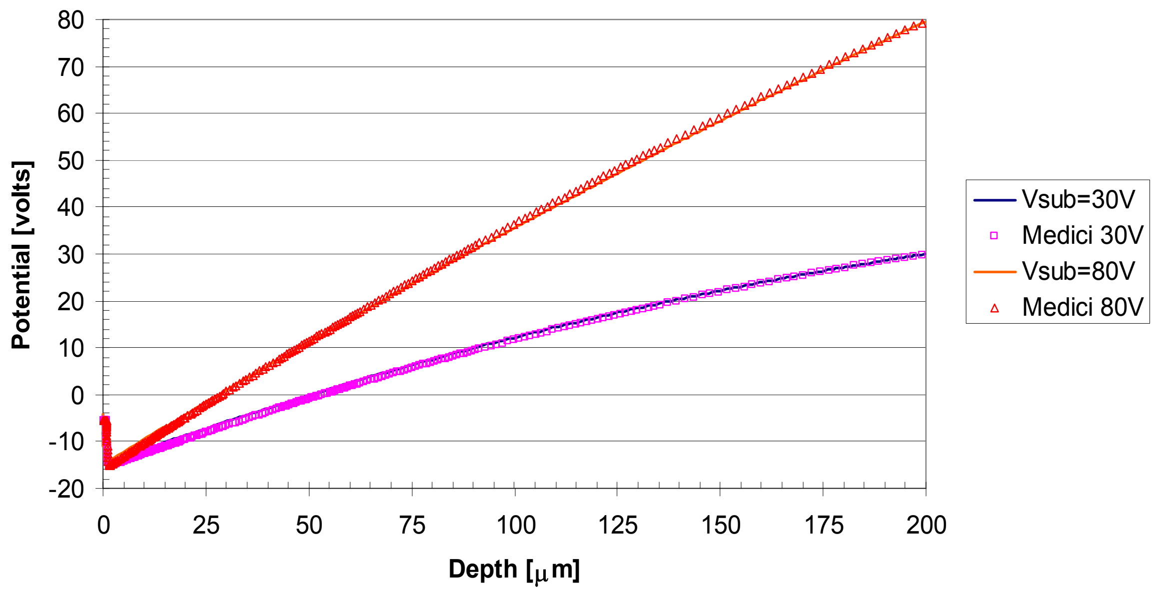
Fully depleted, back illuminated CCD



1) Conventional CCD fabricated on thick, high-resistivity silicon substrate
2) Substrate bias voltage used to fully deplete substrate
3) High near-infrared QE and elimination of fringing
4) Control of PSF via thickness and substrate bias voltage
5) P-channel CCD – improved radiation hardness



MEDICI 2-D simulation



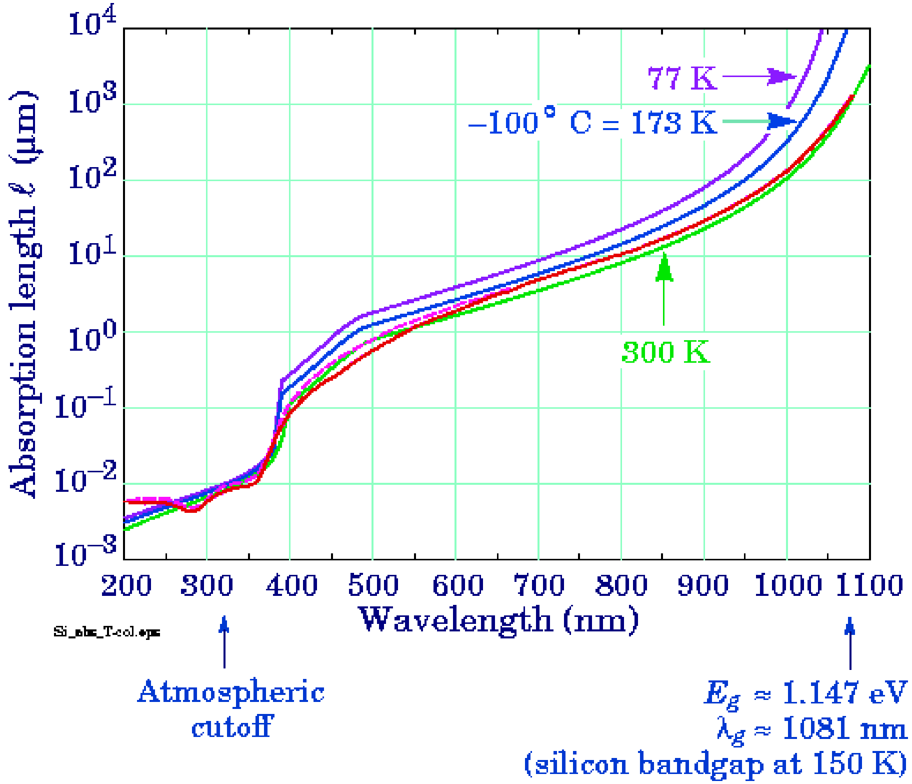
Potential versus depth along center of pixel
1-D potential calculations and Medici simulation

S. E. Holland, D.E. Groom, N.P. Palaio, R.J. Stover, M. Wei,
IEEE Trans. Elec. Dev., vol. 50, no. 1, p. 225, January 2003

LBNL CCDs: Technical Advantages

- Wavelength Coverage
  - —LBNL CCDs have extended quantum efficiency out to 1000 nm
- Radiation Tolerance
  - — CCDs have been the detectors of choice for astronomy. But their charge transport mechanism has been very sensitive to radiation damage in space.
  - — LBNL CCDs are more radiation tolerant than previous devices.
- Small Pixel / Reduced Diffusion
  - —LBNL CCD pixel scale is under our control - 10.5 μm pixels in visible is a good match to the 18 um pixel sensors in the near-infrared (larger diffraction)
  - — Diffusion in device should be smaller than pixel size
    - Unique control of PSF in LBNL CCDs through bias voltage
    - Have measured PSF as small as 6.4 μm on 280 μm thick device
    - Scaling with thickness (1/d) and HV (1/√HV) suggests 4 μm is achievable for 200 μm thick device operated at 100 V. This is approximately a factor 2 smaller than “Brand-X” CCDs.

Quantum efficiency issues

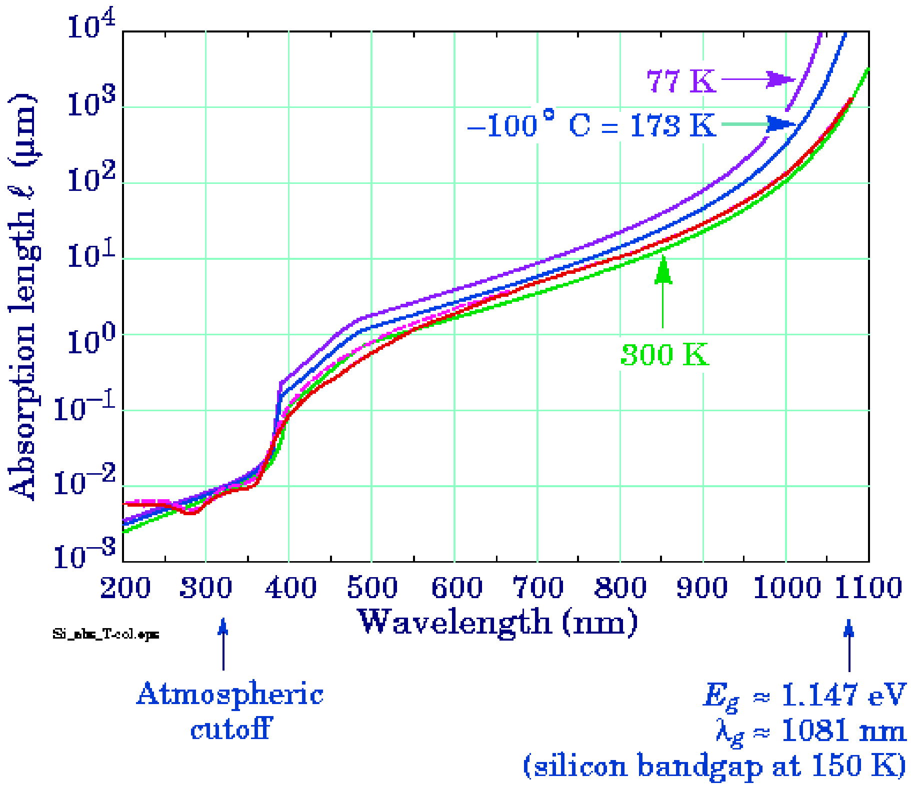


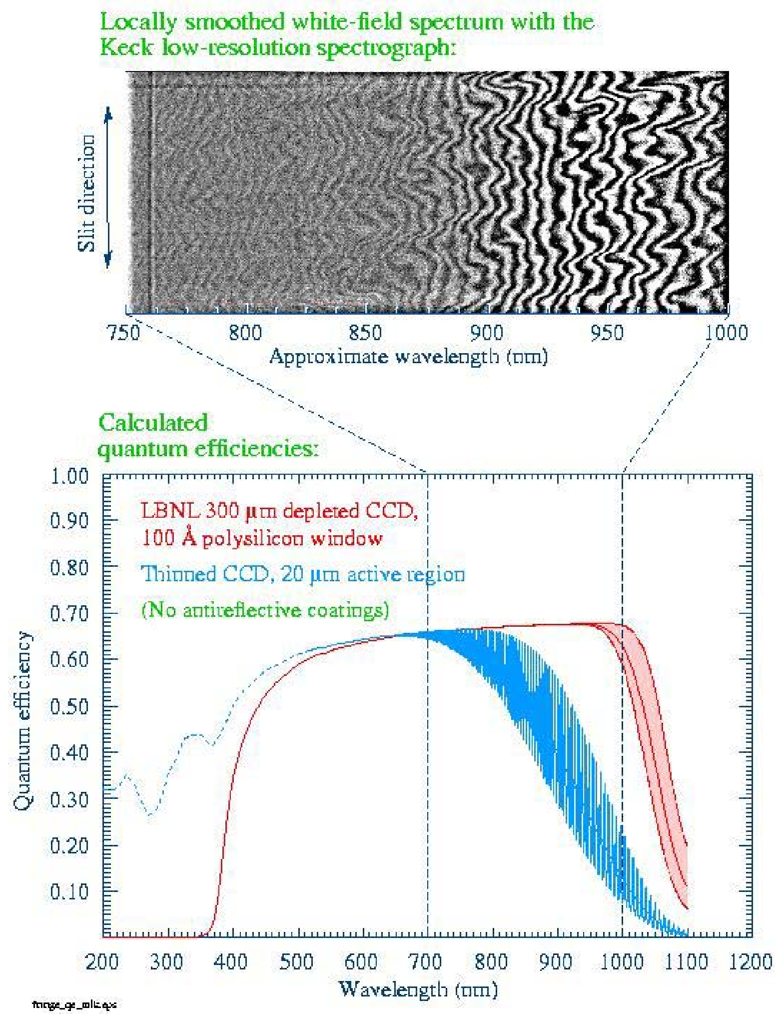
$$I = I_o \exp(-\alpha x)$$

α = Absorption Coefficient

- Implications
  - — Blue response requires back illumination due to absorption in polysilicon gates
    - Commercial digital camera/camcorder CCD's typically have a photodiode region in the pixel for blue response, resulting in less than 100% fill factor
  - — A thin optical window is required for good blue response
    - $l \sim 0.1$ μm at 400 nm
  - — Red response requires a thick depletion region

Fringing and Quantum Efficiency

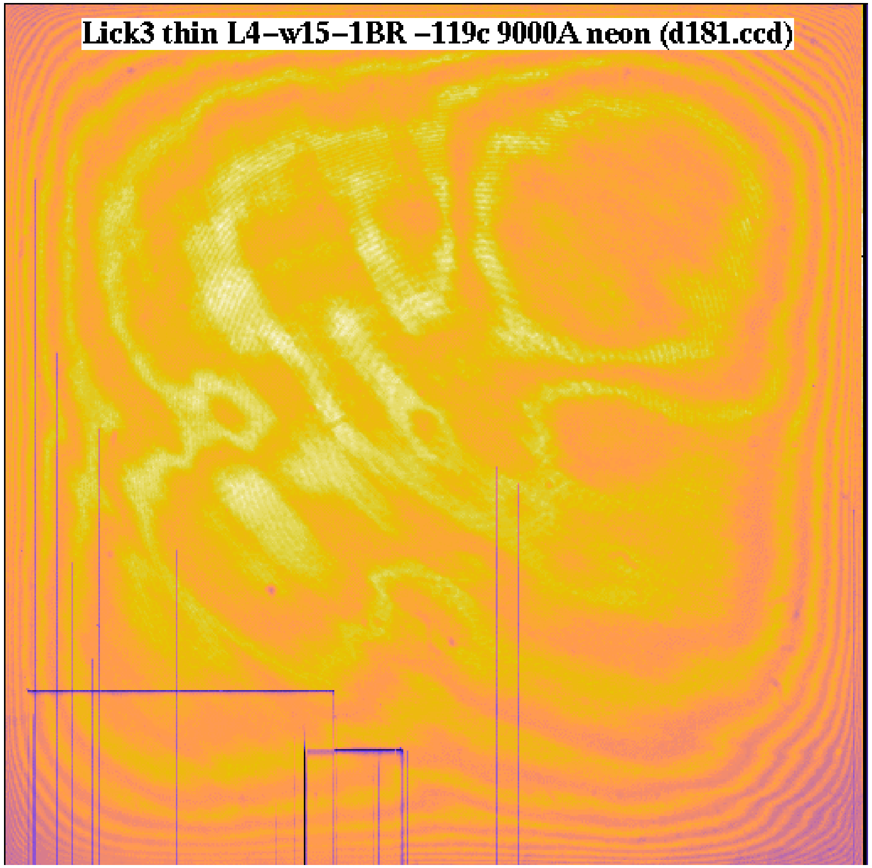




D. Groom et al, "Quantum efficiency of a back-illuminated CCD imager: an optical approach," Proc. SPIE, 3649, 80, 1999.

Motivation for LBNL CCD Development

- LBNL Supernova Cosmology Project
  - —Cosmological studies of distant, red-shifted Type Ia SN
- Existing scientific CCD's have poor red response and suffer from fringing at near-infrared wavelengths



Multiply-reflected light leads to fringing patterns when the absorption length is comparable to the CCD thickness. Courtesy Richard Stover of Lick Observatory.

9000A flat field

LBNL MicroSystems Laboratory

LBNL Microsystems Laboratory - Class 10 clean room, full CCD fabrication except ion implantation for 100 mm wafers, some 150 mm capability

CCD's fabricated at LBNL MSL are in use at the National Optical Astronomy Observatory and Lick Observatory

Thermco furnaces at LBNL Microsystems Laboratory

150 mm lithography tool at LBNL

LBNL CCD Production Steps

- **Front-side processing:**
  - —standard CMOS process, 8 masks
- **Back-side processing:**
  - —Thin wafers
  - —Backside contact: thin, in-situ doped polysilicon (ISDP)
    - requires high temperature (600 C) furnace
  - —Anti-reflective coating
- **Complication: final front-side processing step is metallization, but Al melts at temperatures required for ISDP**
  - —must perform metallization after thinning and ISDP
  - —requires additional handling of thinned wafers
  - —or process changes (eg high-temp metal such as TiN)

LBNL CCDs: Technical Issues

- Device availability
  - —LBNL CCDs used for scientific imaging to date have been manufactured in the LBNL Microsystems Lab
  - —Small R&D facility, not ideal for mass production
  - —Large scale production of LBNL CCDs requires an industrial partner
  - —Commercialization of the LBNL CCD fabrication process is a major SNAP goal and has been in progress for ~3 years with DALSA Semiconductor
  - —**Goal is to produce CCDs in quantity with ALL of the following properties:**
    - **large format**
    - **200 um thickness**
    - **high yield for scientific grade devices**

LBNL CCD Process Flow

All processing at LBNL on 4” wafers

Front-side process at commercial foundry

thin, ISDP, contact etch & metallization, AR coat at LBNL

etch & metallization with TiN at foundry

thinning, ISDP, etch, metallization & AR coating at foundry

ISPD, contact etch & metallization at foundry

thin, ISDP and AR coating at LBNL

“LBNL MSL”

“Hybrid Business Model”

“Refractory metal”

“Fully commercialized”

“Front illuminated”

Thinned (200 um), back-illuminated CCD

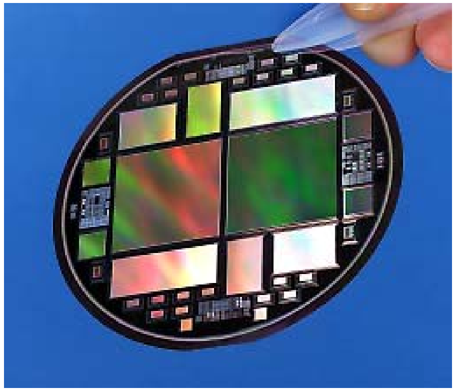
Thick, front-illuminated CCD

(QC, HV testing, irradiation)

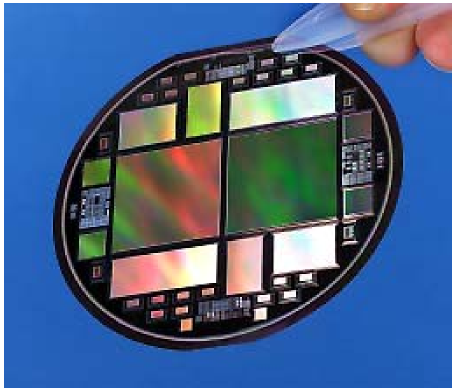
Existing formats

LBNL CCD evolution

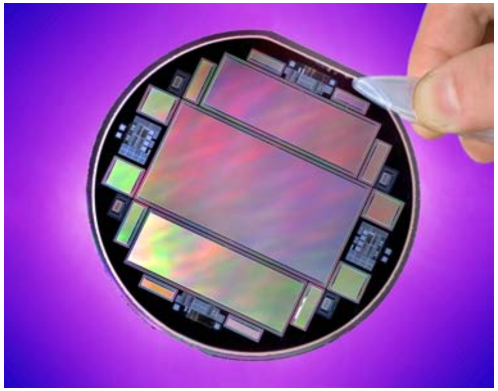
100 mm LBNL-fabbed 2kx2k



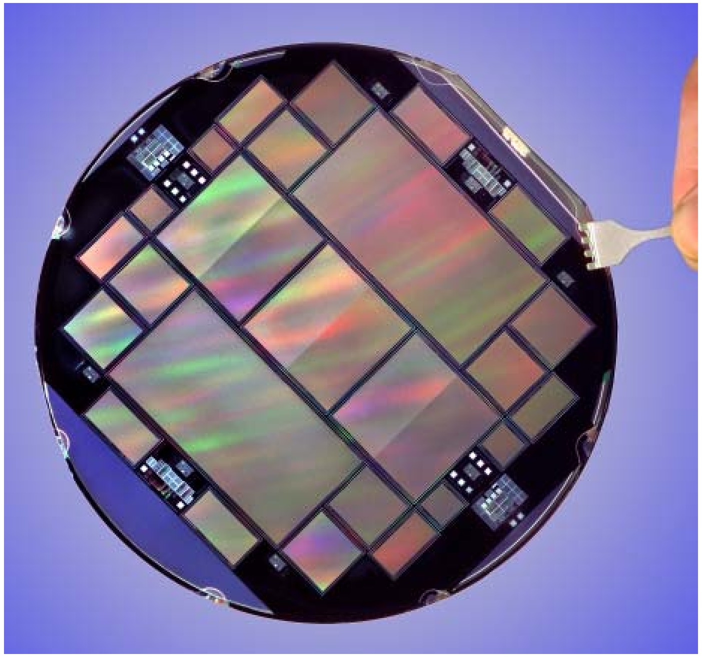
100 mm DALSA 2kx2k



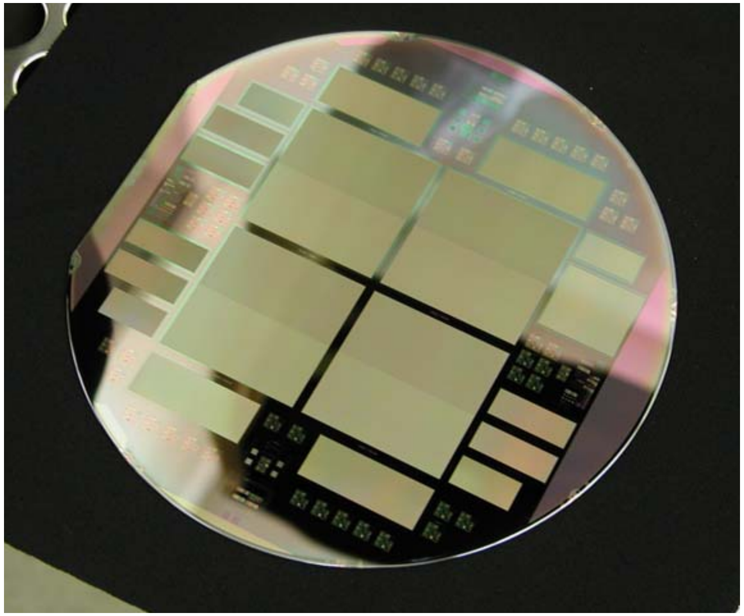
100 mm LBNL-fabbed 2kx4k



150 mm DALSA 2kx2k & 3kx3k



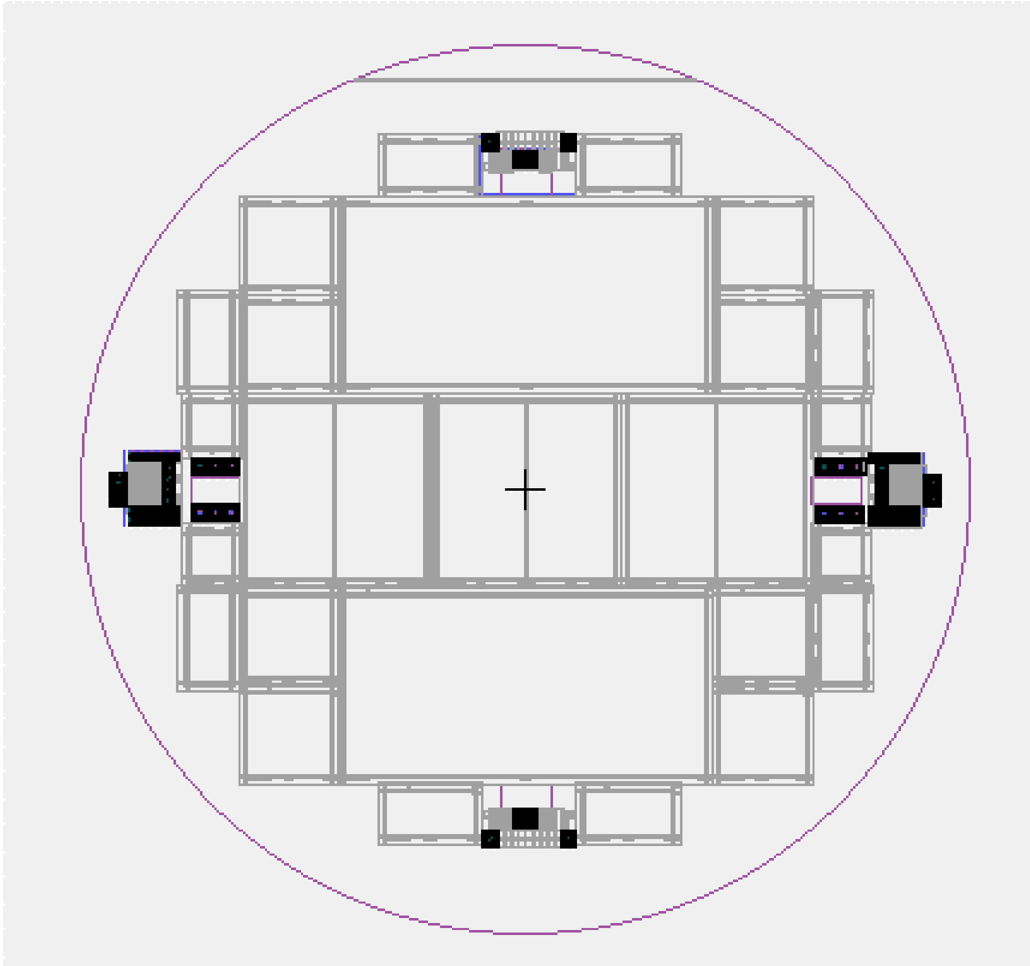
150 mm LBNL/DALSA 3.5kx3.5k



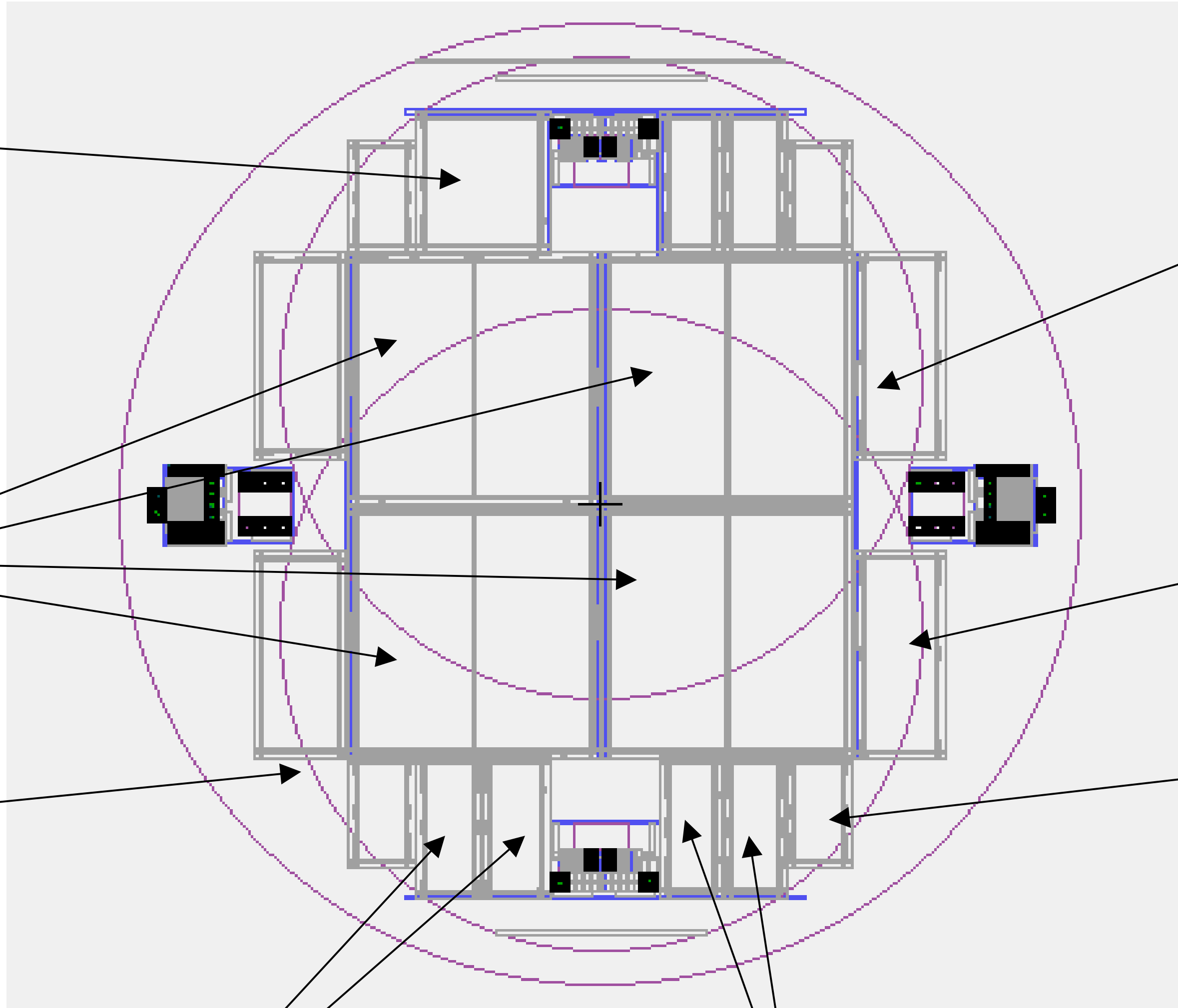
150 mm CCD layout

Includes

1) 982 x 935 (15 μm)^2
2) 1230 x 1170 (12 μm)^2
3) 1402 x 1336 (10.5 μm)^2
4) 1636 x 1560 (9 μm)^2
5) 2520^2 (12 μm)^2
6) 2880^2 (10.5 μm)^2
7) 2048 x 4096 (15 μm)^2
8) 512^2 & 1024 x 512 (15 μm)^2
   Amplifier studies (noise)
9) 1200 x 600 (15 μm)^2
   2-stage amplifiers for
   high-speed readout



Layout for DALSA run in progress



SNAP 18 μm
pixel spectrograph
CCD

800 x 1980
NOAO MARS
(2x, 1 12 μm pixel
with design for high
voltage)

SNAP 3512^2

470 x 1264 24μm
Lick Guider (2x)
(1 with 2-stage amp)

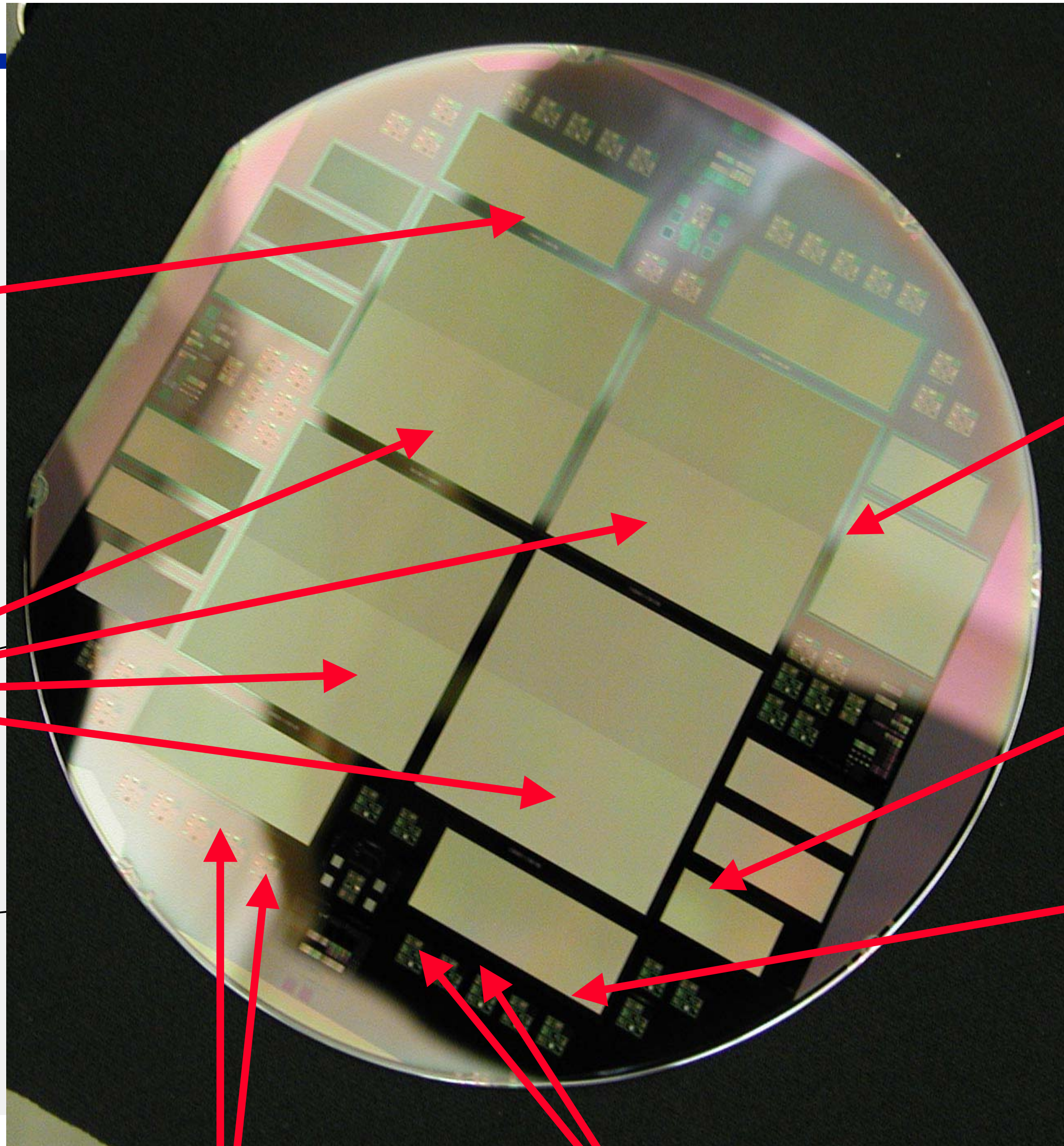
Template for
100 mm cutdown
if necessary

1k x 512 (4x)

SNAP 9 μm
Pixel spectrograph
CCD 2226 x 868

2210 x 802 9μm
2-stage amps (4)
~ 20 fps (4x)

Layout for current DALSA run



SNAP 18 μm pixel spectrograph CCD

800 x 1980 NOAO MARS (2x, 1 12 μm pixel with design for high voltage)

SNAP 3512^2

470 x 1264 24μm Lick Guider (2x) (1 with 2-stage amp)

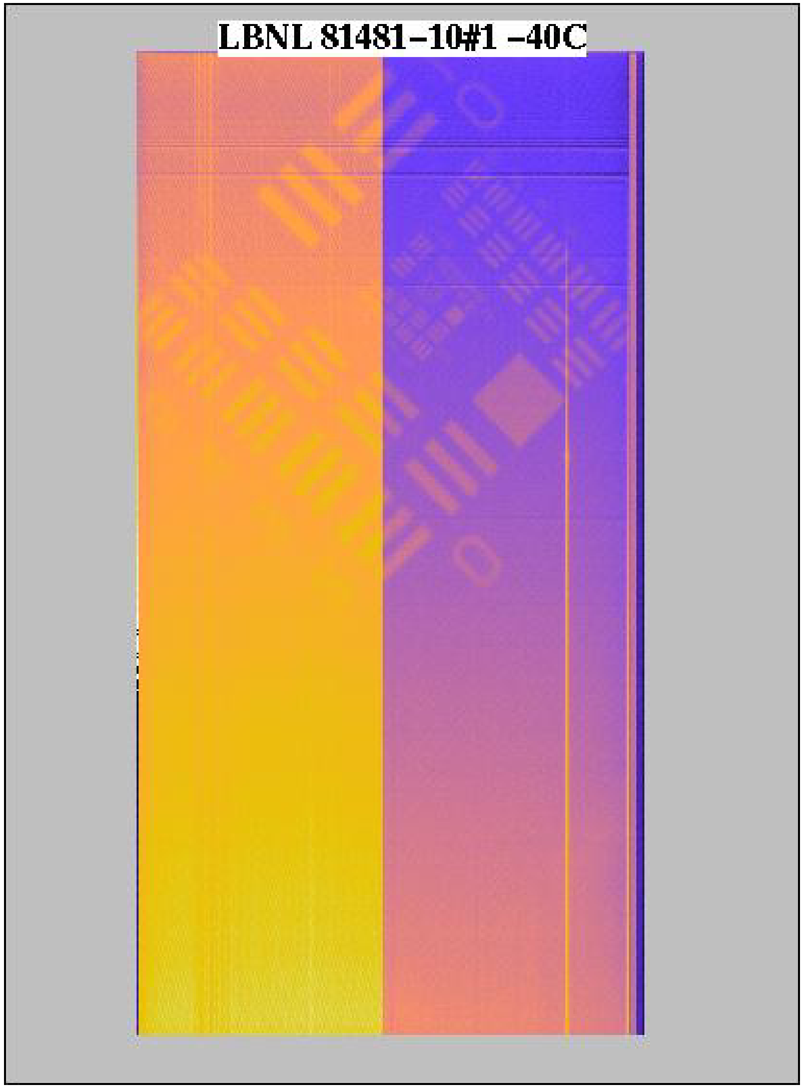
Template for 100 mm cutdown if necessary

1k x 512 (4x)

SNAP 9 μm Pixel spectrograph CCD 2226 x 868

2210 x 802 9μm 2-stage amps (4) ~ 20 fps (4x)

Refractory metal results



4k x 2k (15μm pixel)

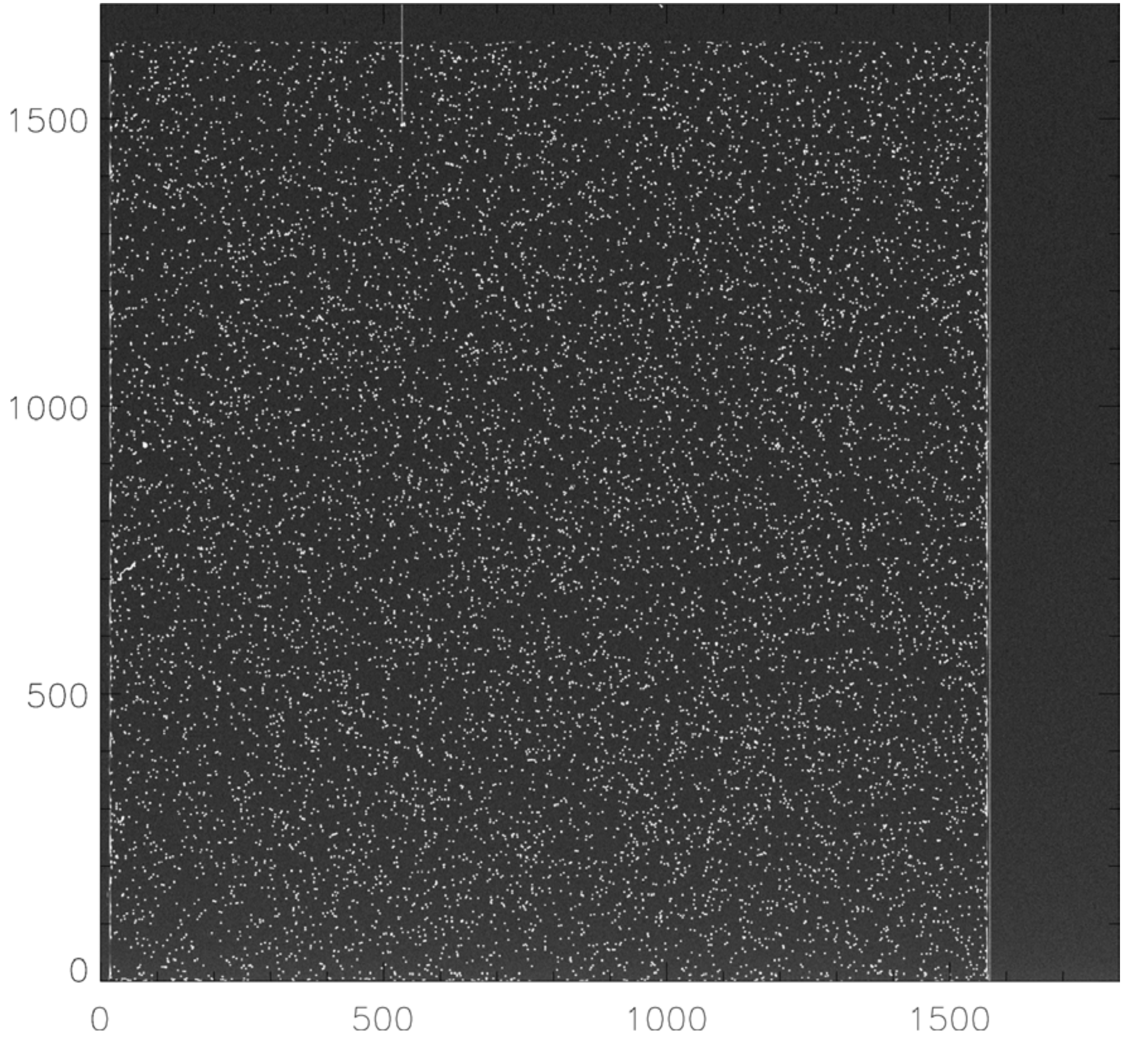
Wafer probe image at –40C

Readout ~ 220 kpixels/sec
~ 17 s readout with two amplifiers

1 μs integration time (reset and signal)
4.5 μs per pixel

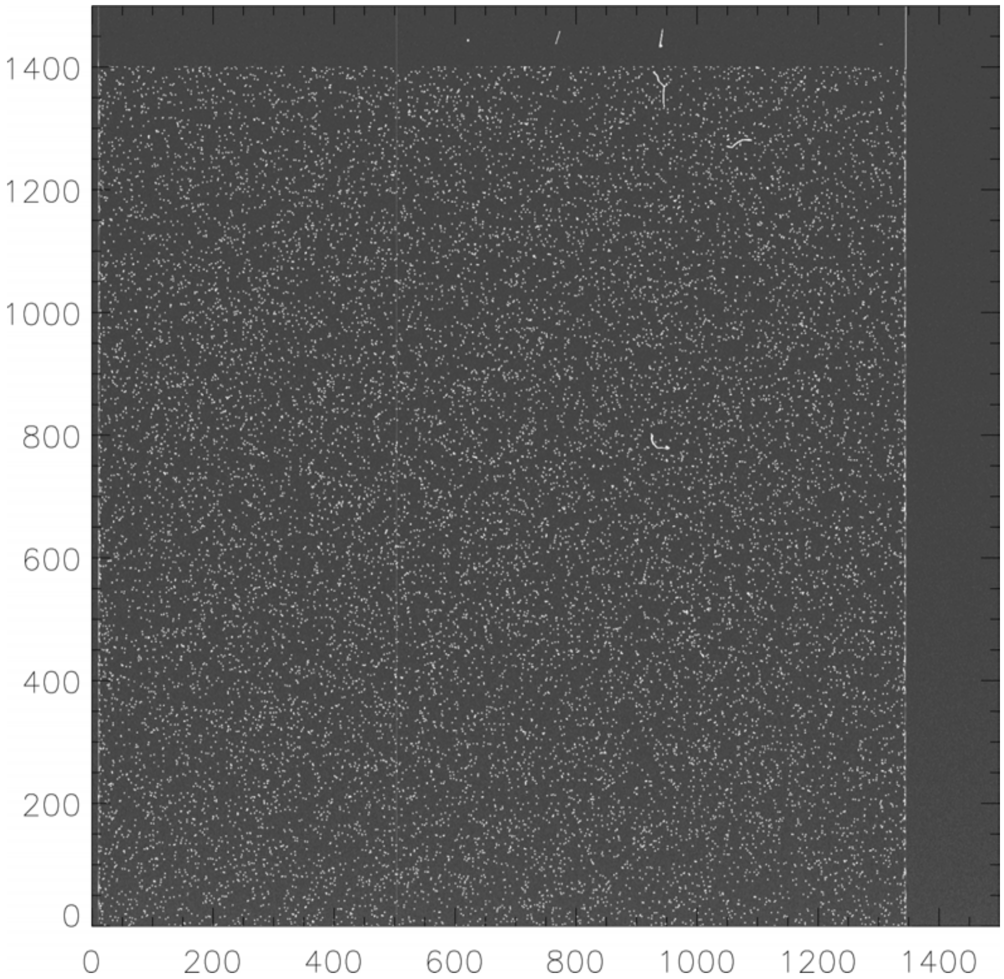
Lick guider camera readout

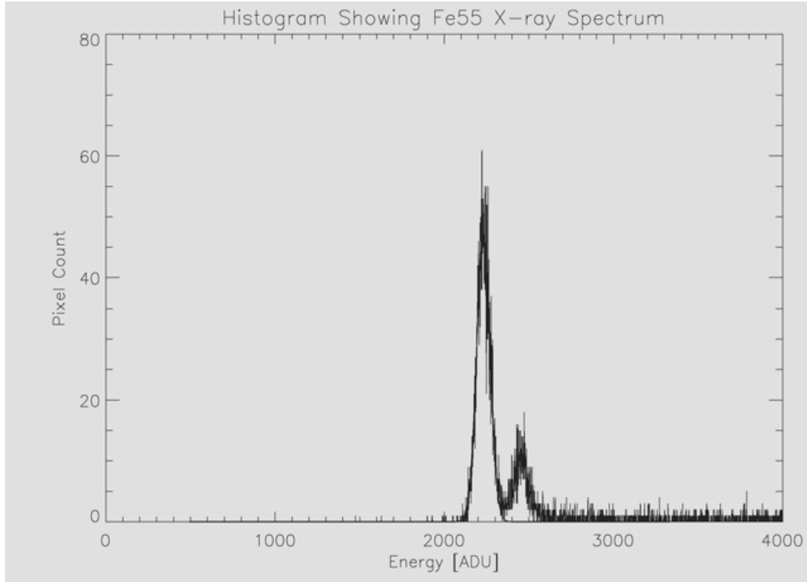
Refractory metal CCD 81481.10.25



X-ray image of CCD measured at substrate voltage, V_{sub} = 50V, temperature –135C. Measured gain from the x-ray analysis was 1.77 adu/e-. Only one hot pixel at ~(1500,500) can be seen.

LBNL/DALSA CCD - ^{55}Fe X-ray Image

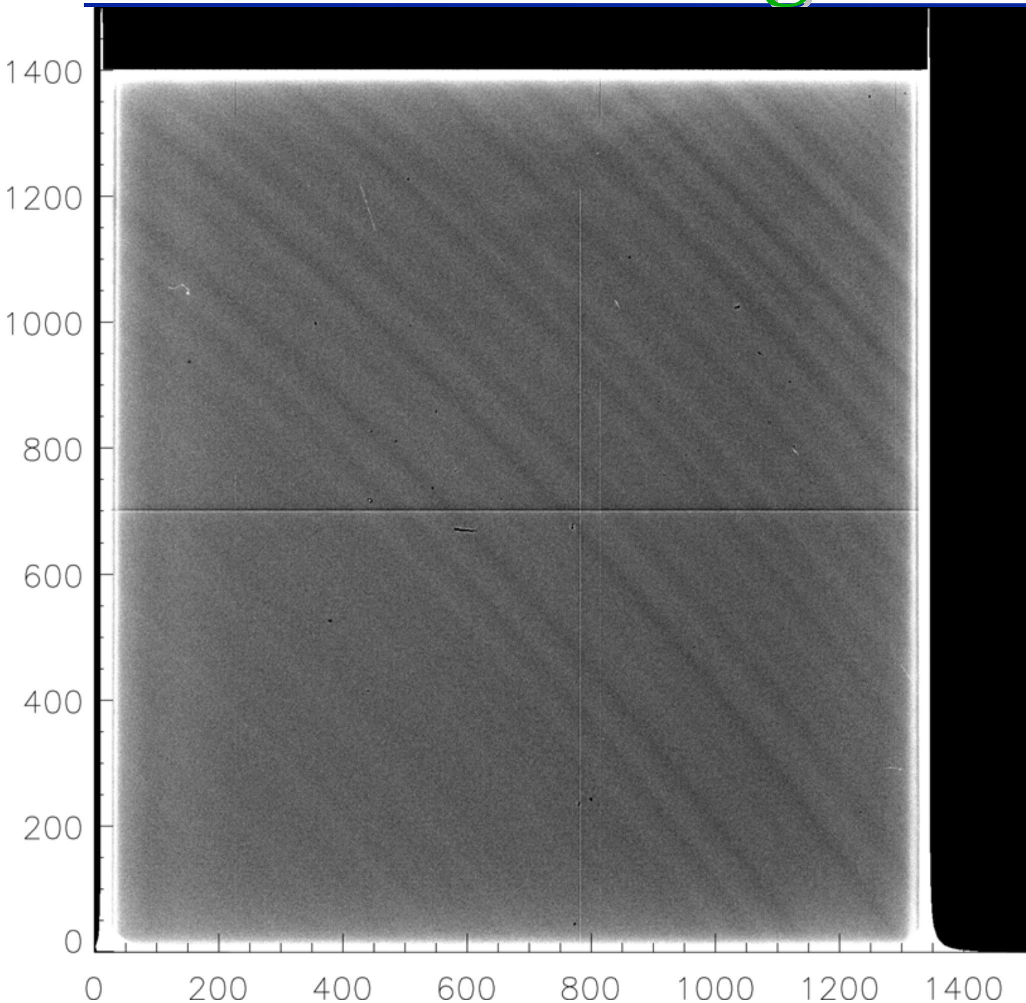


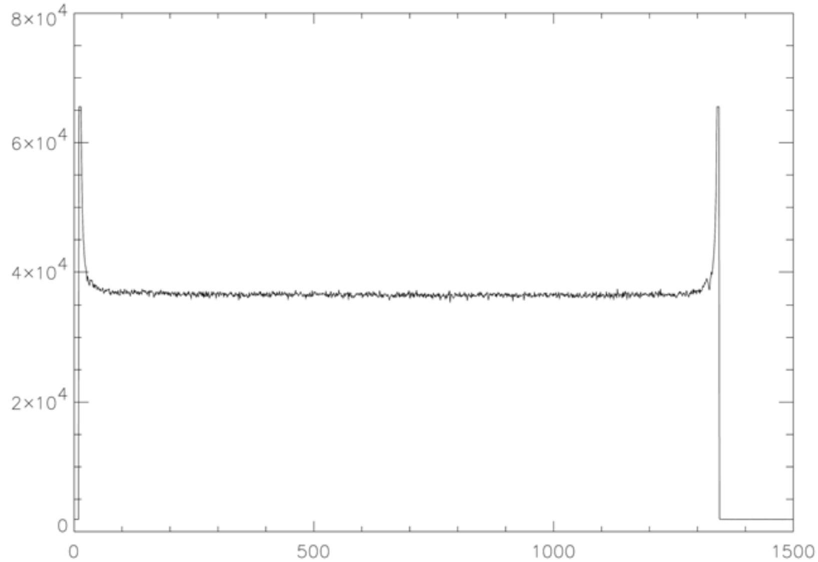


3 x 3 pixel summation

1402 x 1336 (10.5 µm pixel)
Back illuminated
250 µm thick
Operated at 75V (overdepleted) and –140C

LBNL/DALSA CCD - Flat Field Image





Flatfield image taken with green (500 nm) filter. Average intensity within image 25000 e- The image shows a few bright columns, a line at the boundary between the FS and V registers and grinding/polishing marks but no no backside processing damage. Similar results found for blue filter. (sky 34000, span 4000)

In use

LBNL CCD's at NOAO

Science studies to date at NOAO using LBNL CCD's:

1) Near-earth asteroids
2) Seyfert galaxy black holes
3) LNBL Supernova cosmology

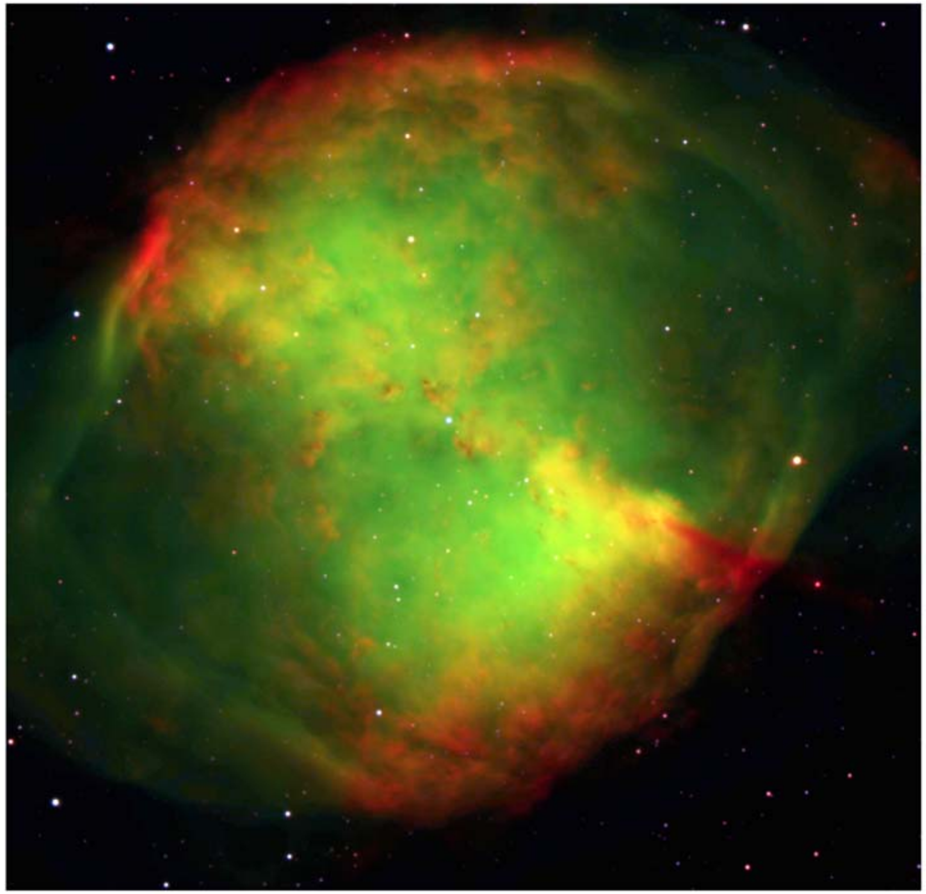
Cover picture taken at WIYN 3.5m with LBNL 2048 x 2048 CCD (Dumbbell Nebula, NGC 6853)
Blue: H-α at 656 nm
Green: SIII at 955 nm
Red: 1.02 μm

New instrument at NOAO available in shared risk mode using LBNL CCD's – Multi-Aperture Red Spectrometer (MARS)

LBNL CCD's scheduled for 37 nights during 2002A (Jan – July 2002)

See September 2001 newsletter at http://www.noao.edu

Visible vs Near-IR imaging



Planetary Nebula NGC 6853 (M 27) - VLT UT1+FORS1

ESO PR Photo 38a/98 (7 October 1998)

LBNL 2k x 2k results

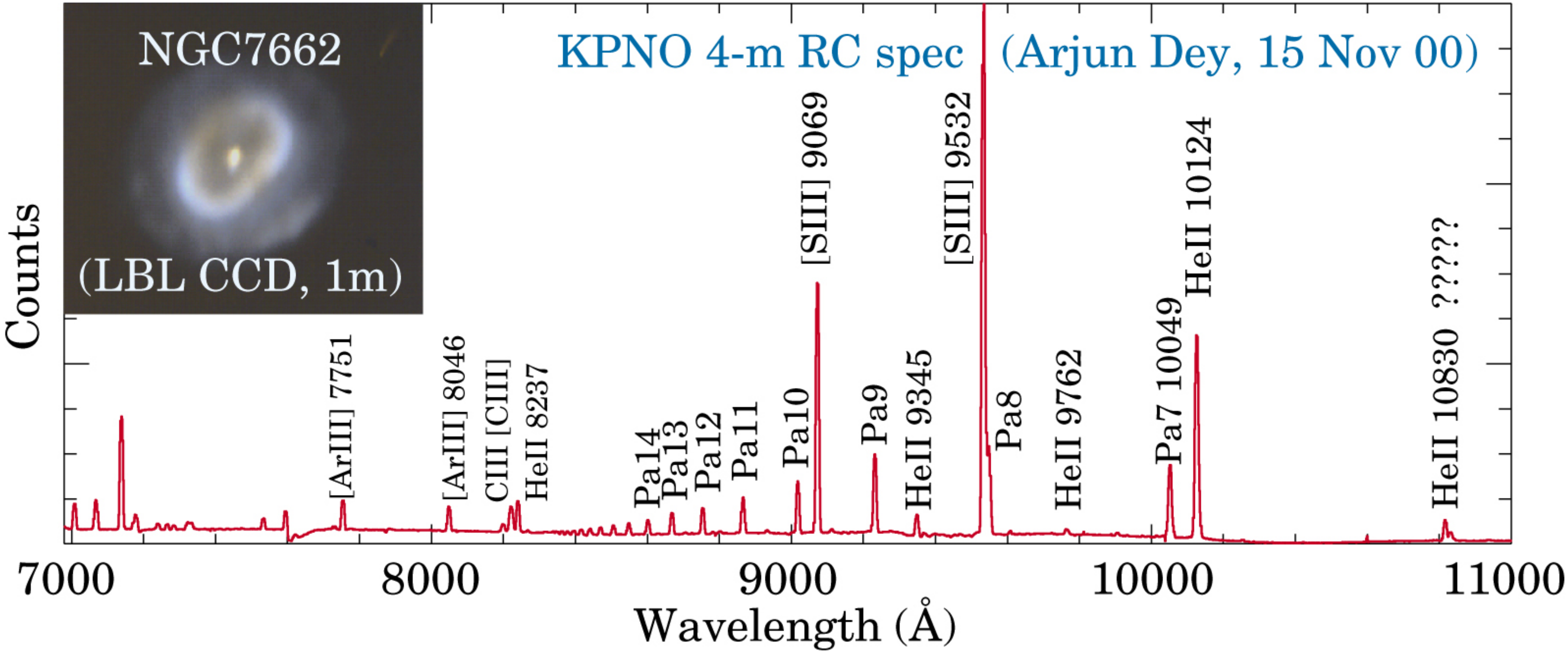
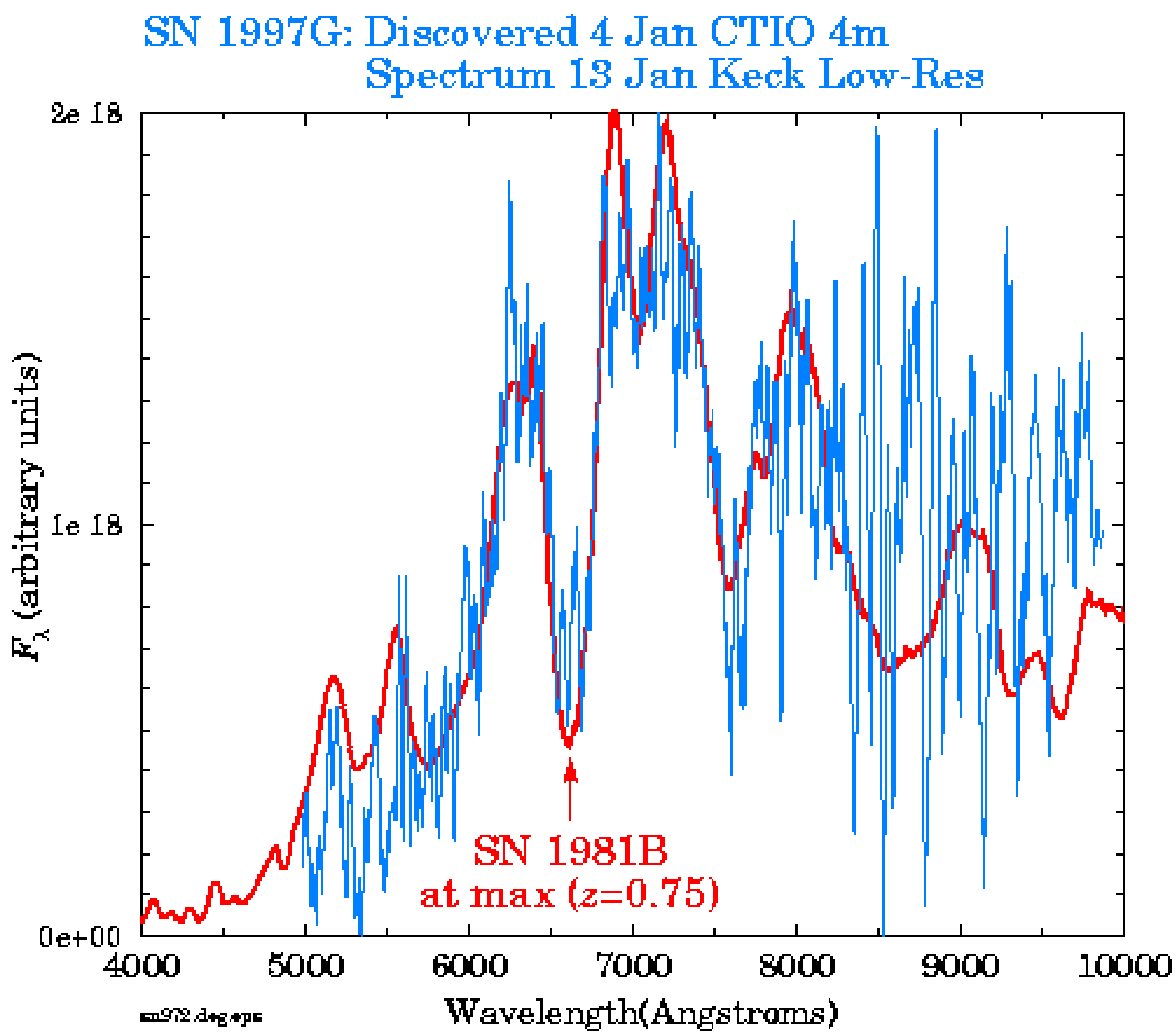
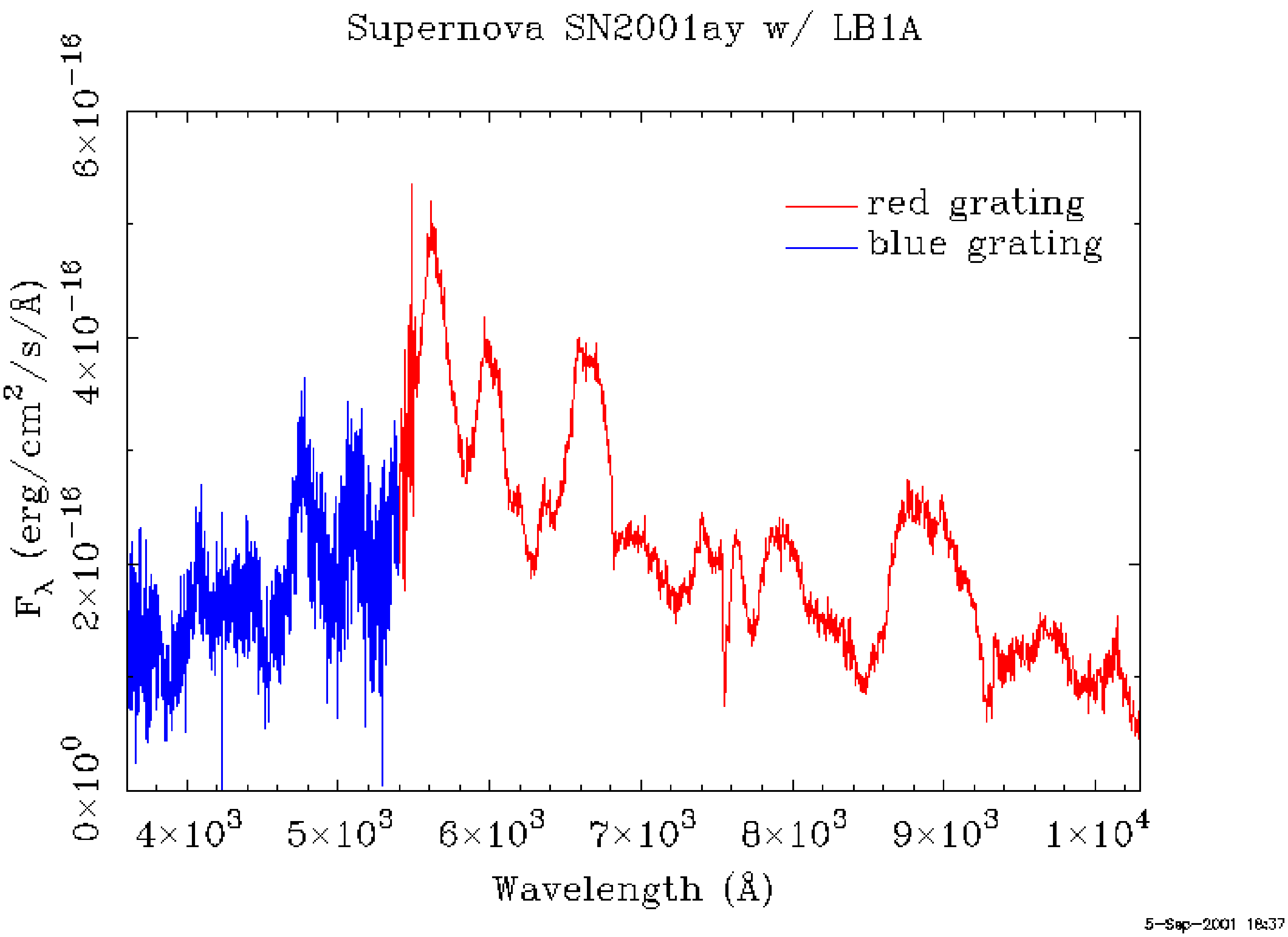


Image: 200 x 200 15 μm LBNL CCD in Lick Nickel 1m.
Spectrum: 800 x 1980 15 μm LBNL CCD in NOAO KPNO spectrograph.
Instrument at NOAO KPNO 2nd semester 2001 (http://www.noao.edu)

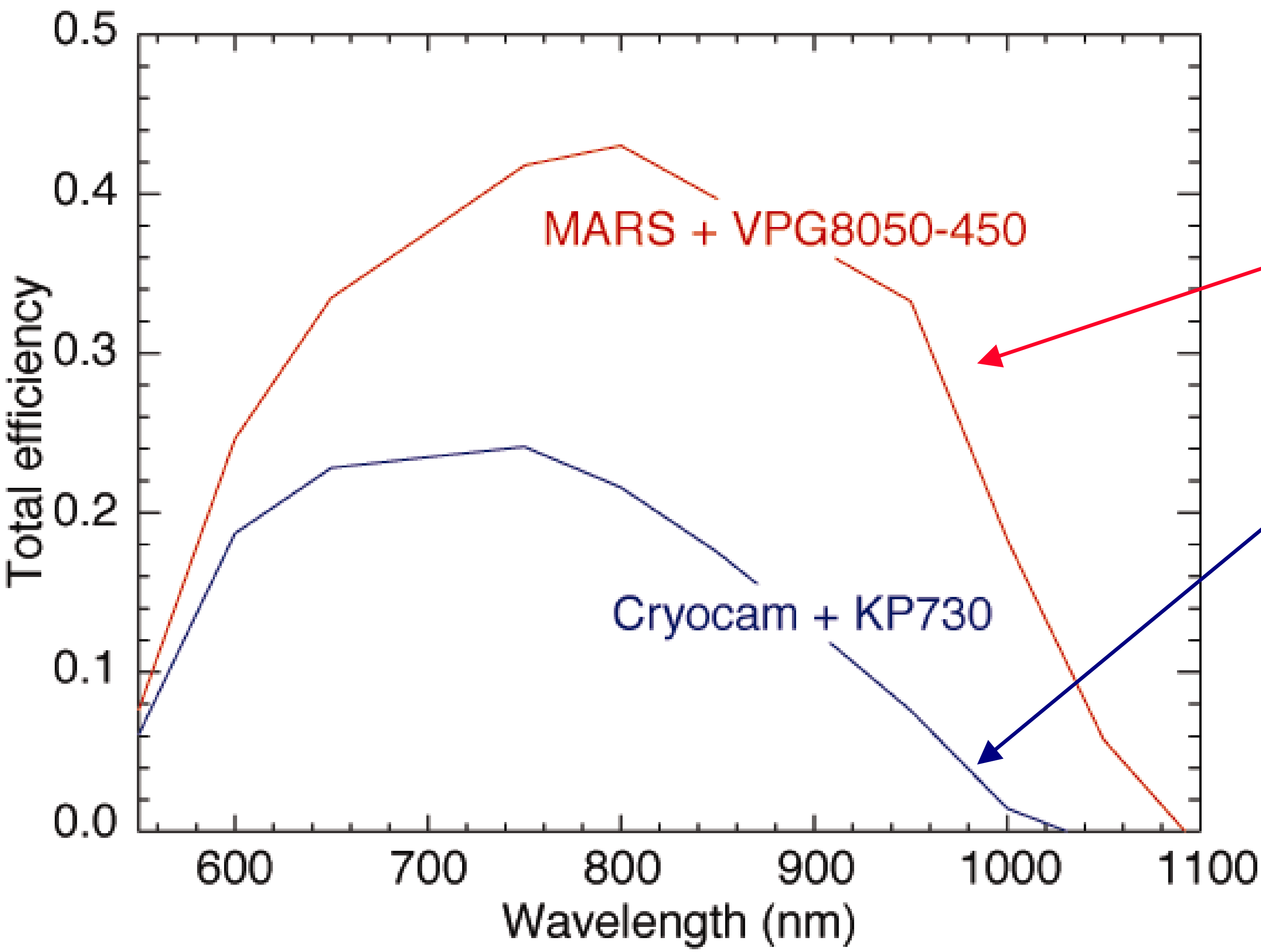
SCP SN follow up spectroscopy at Keck



SCP SN spectrum with LBNL CCD (NOAO)



NOAO Multi-Aperture Red Spectrometer

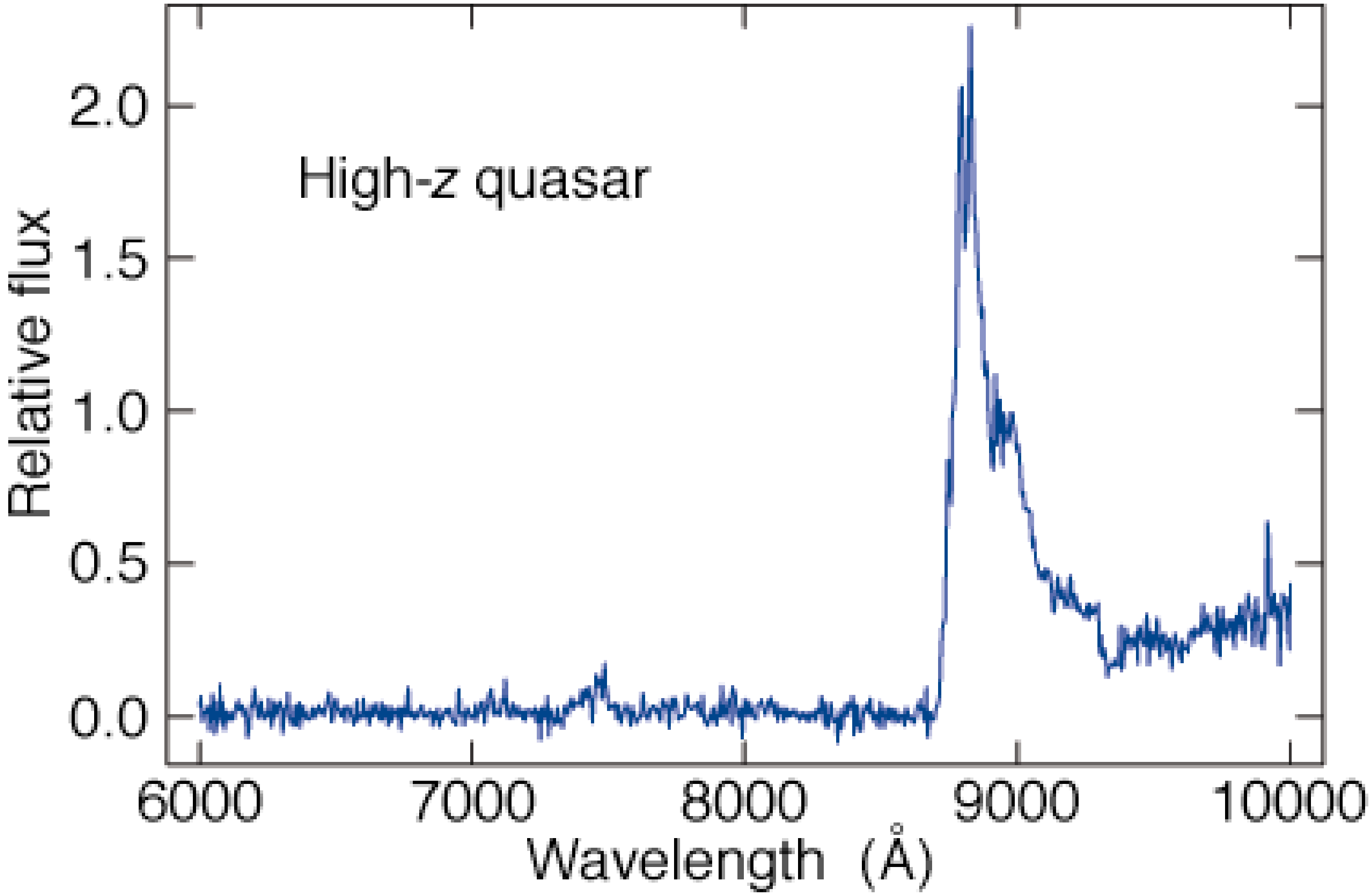


LBNL CCD

Thinned CCD

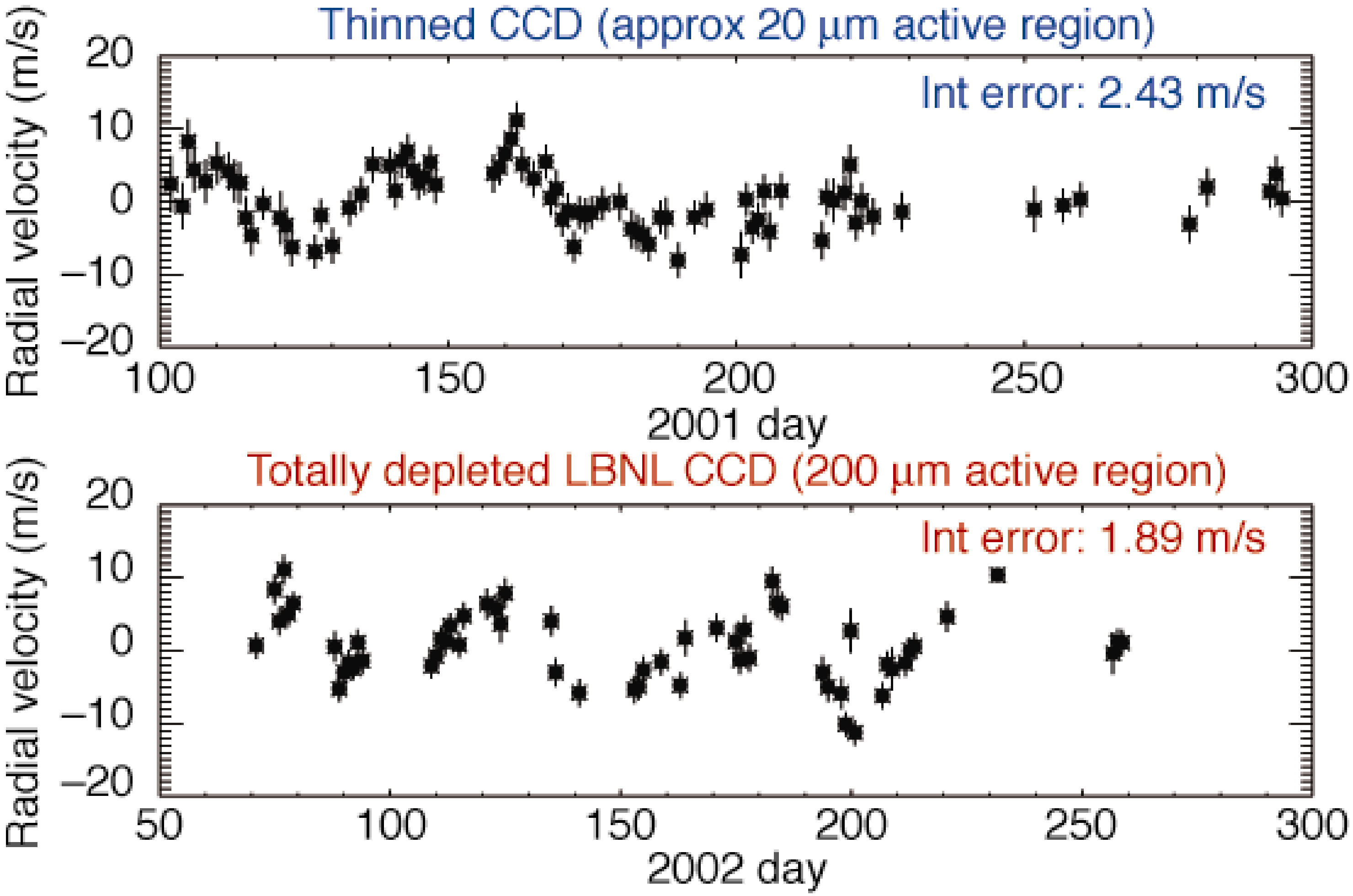
800 x 1980 (15µm pixel) back-illuminated CCD

Science result from NOAO MARS (4 m)



Preliminary data courtesy of Xiaohui Fan, University of Arizona Astronomy Department and the Sloan Digital Sky Survey

Extra-solar planets (D. Fischer, UCB/Lick)



Instrument PSF
1.9 pixels FWHM

Instrument PSF
1.6 pixels FWHM

2k x 2k (15µm pixel)
200 µm thick back illuminated CCD

Peak in power spectrum at 60 days; Amplitude 4 m/s

Improved PSF with LBNL CCD yields ~ 0.6 m/sec improvement in rms uncertainty

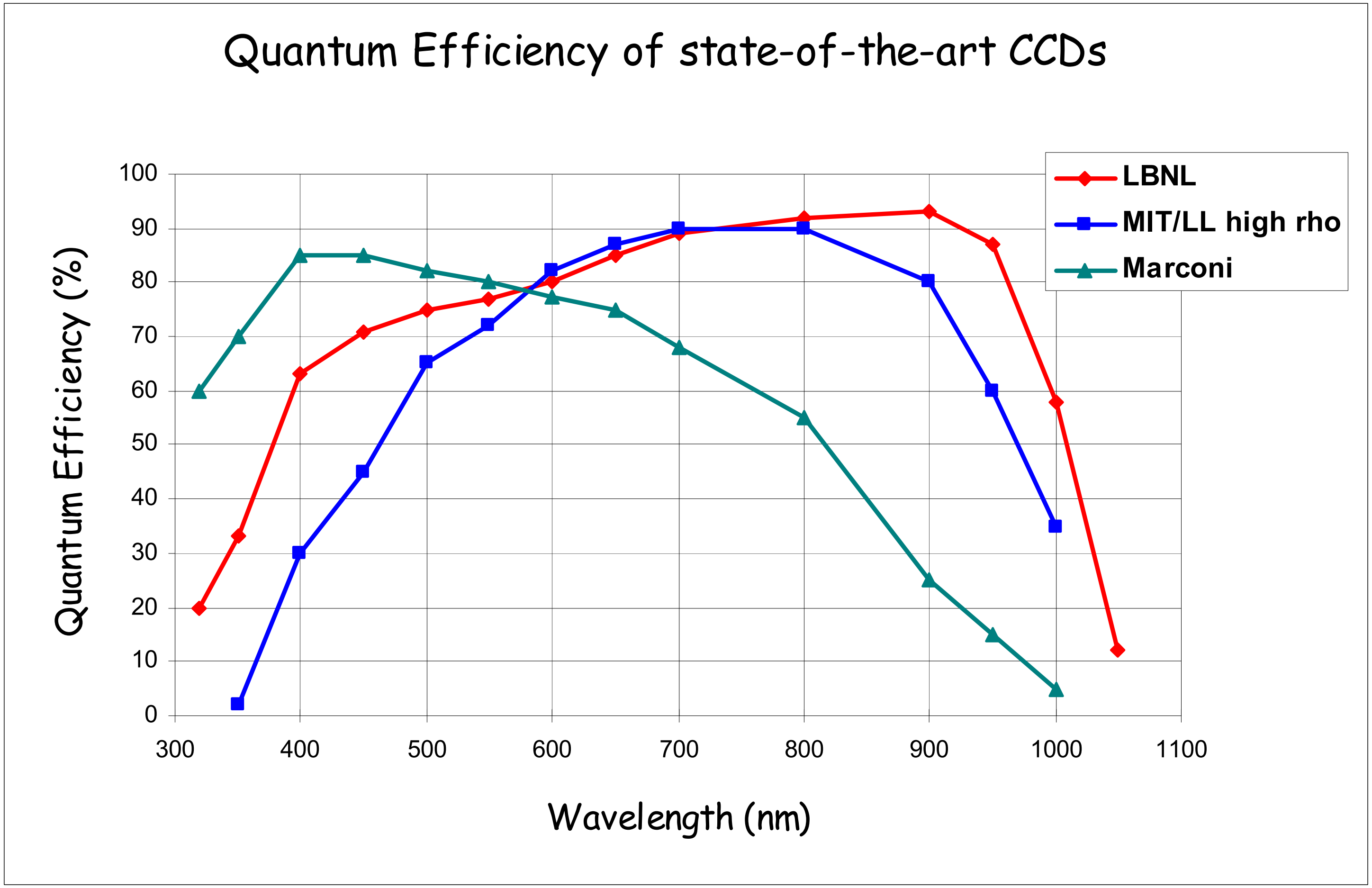
Operation specs

LBNL CCD Performance

• Pixel size	➢ 9, 10.5, 12, & 15 μm devices work
• Well depth	➢ 130 ke for 10.5 μm pixel.
• Linearity	➢ Better than 1%.
• Dark current	➢ 2 e/hr/pixel.
• Sensitivity	➢ 3.5 μV/e
• Persistence	➢ Erase mechanism is effective.
• Read noise	➢ 2 e.
• MOSFET operation	➢ Documented at operating temperature.
• Charge transfer efficiency	➢ CTI ~ 10^{-6} pre-irradiation.
• Quantum efficiency	➢ Extended red performance realized.
• Diffusion	➢ On-going study.
• Intrapixel response	➢ On-going study.
• Fabrication	➢ Partially commercialized.
• Packaging	➢ Underway

R&D areas.

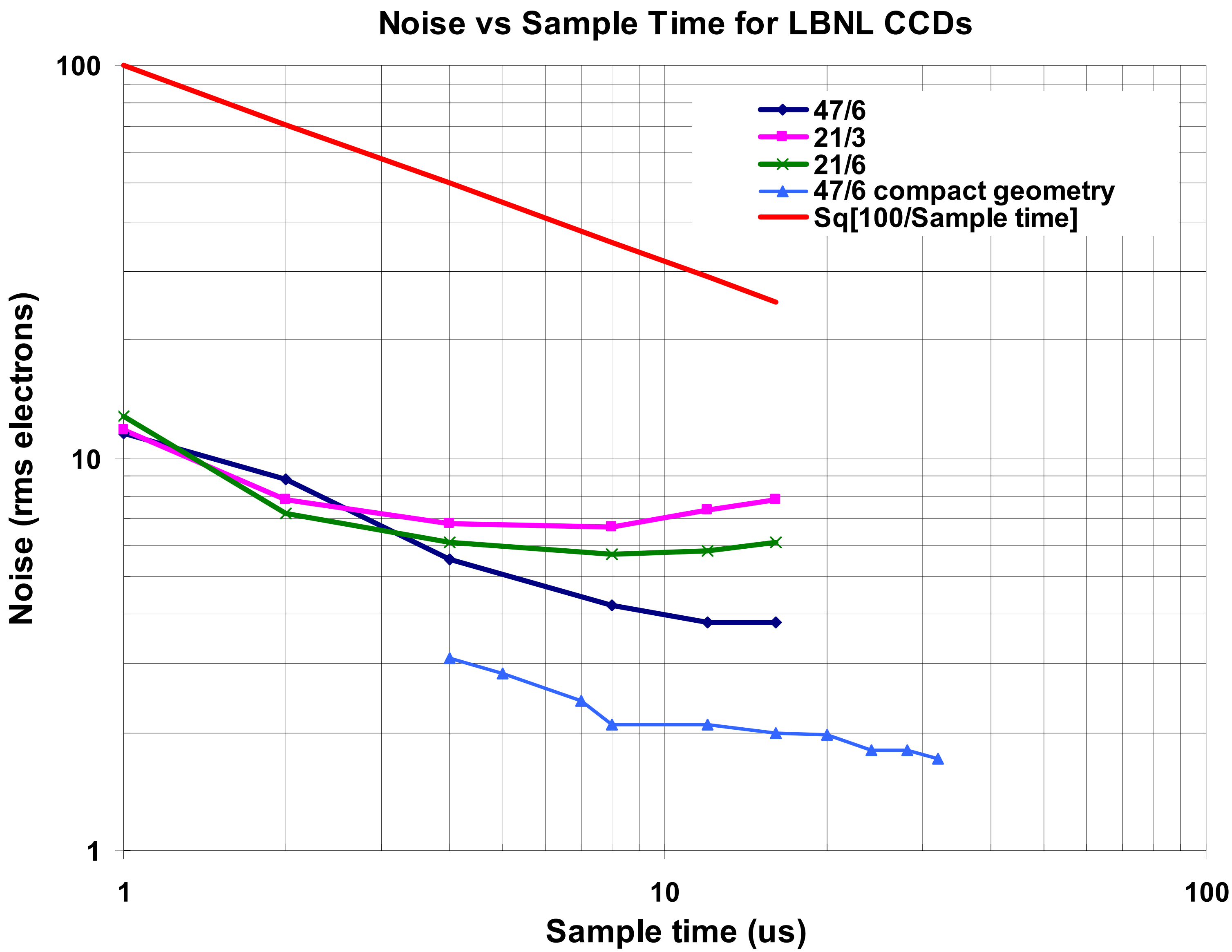
LBNL 2k x 2k Quantum Efficiency



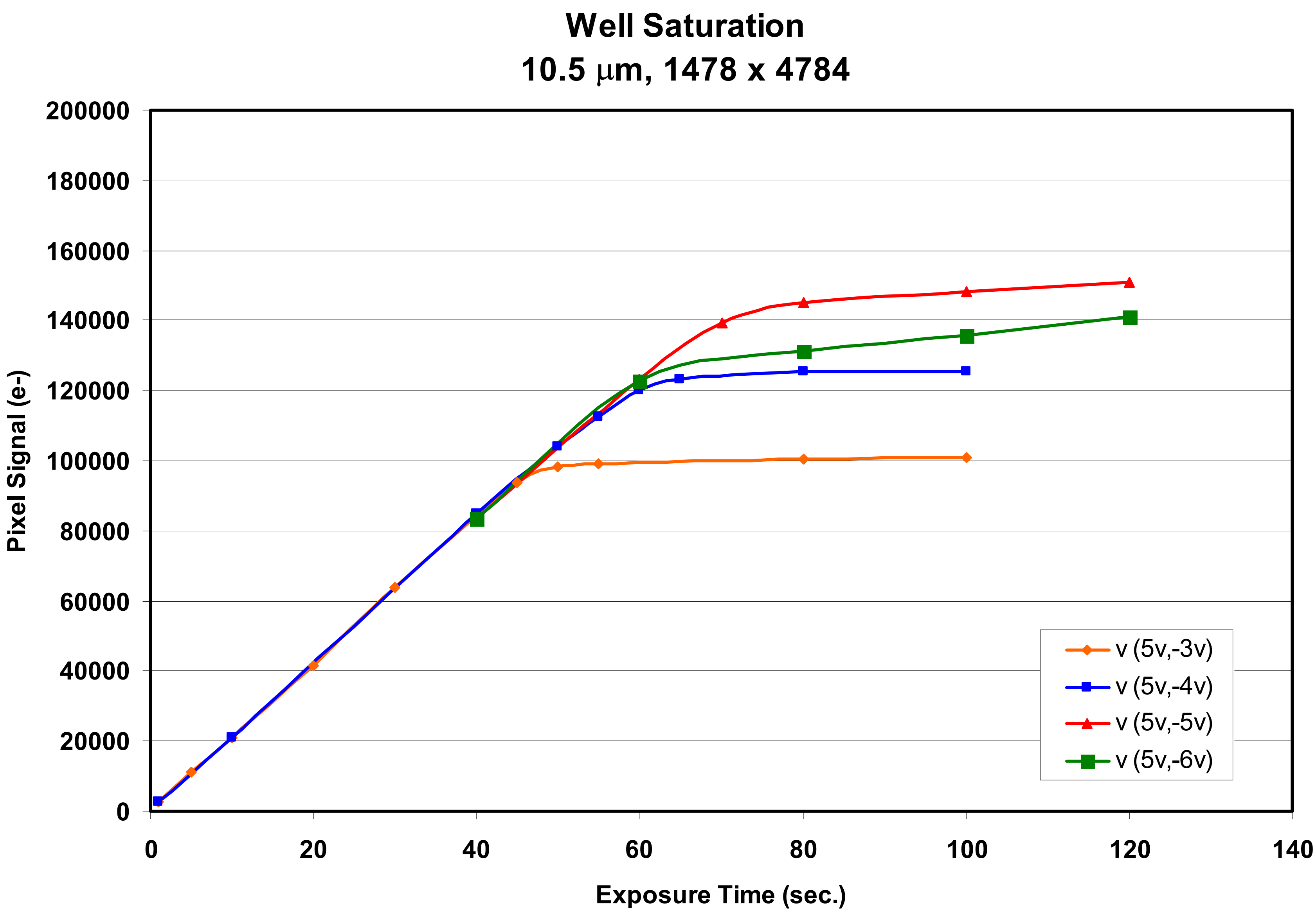
From "An assessment of the optical detector systems of the W.M. Keck Observatory," J. Beletic, R. Stover, K Taylor, 19 January 2001.

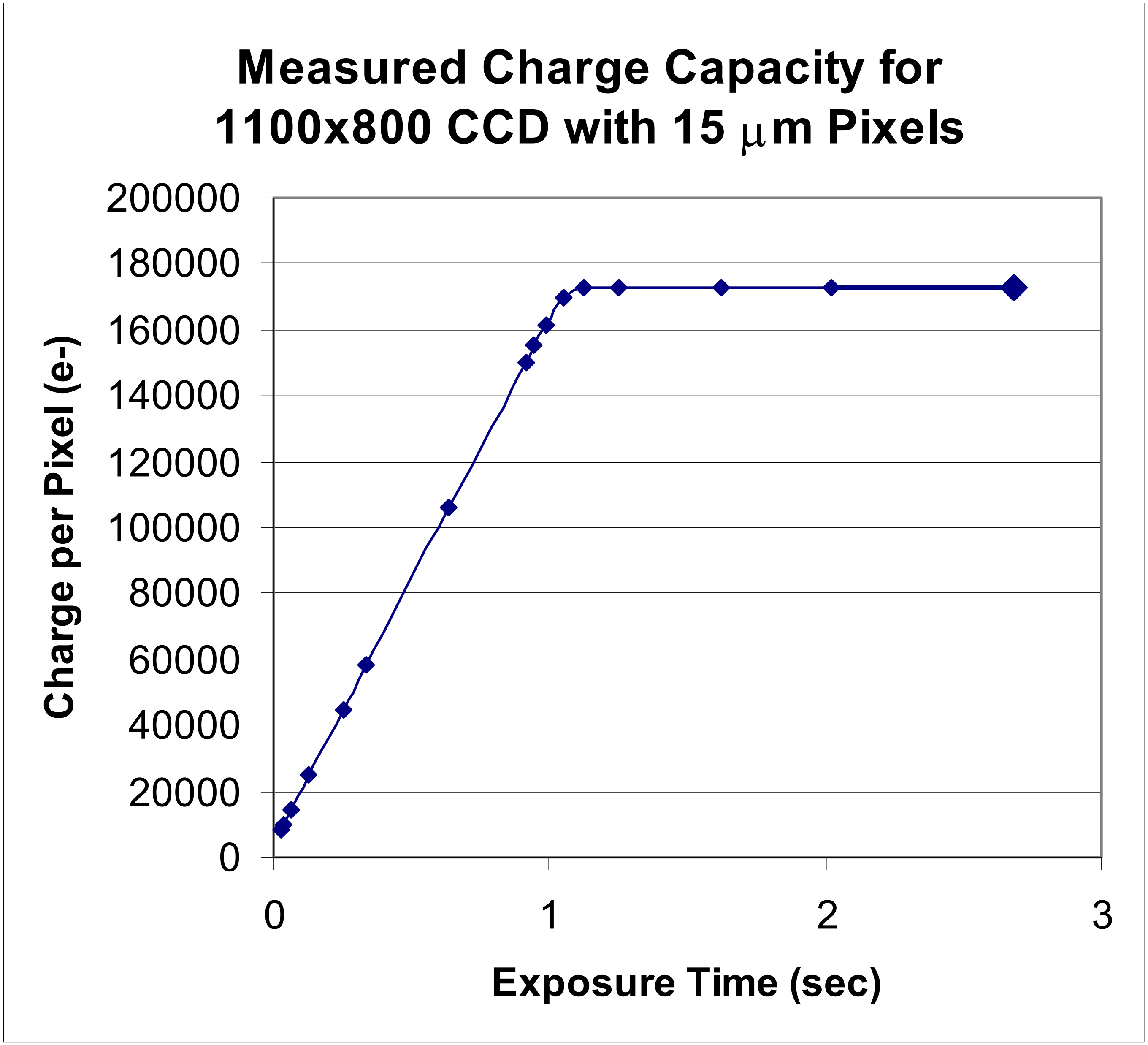
2 layer anti-reflection coating: ~ 600A ITO, ~1000A SiO_2

Read noise


Noise vs Sample Time for LBNL CCDs
100
10
1
1
10
100
Sample time (us)
Noise (rms electrons)
47/6
21/3
21/6
47/6 compact geometry
Sq[100/Sample time]

10.5 μm Well Depth





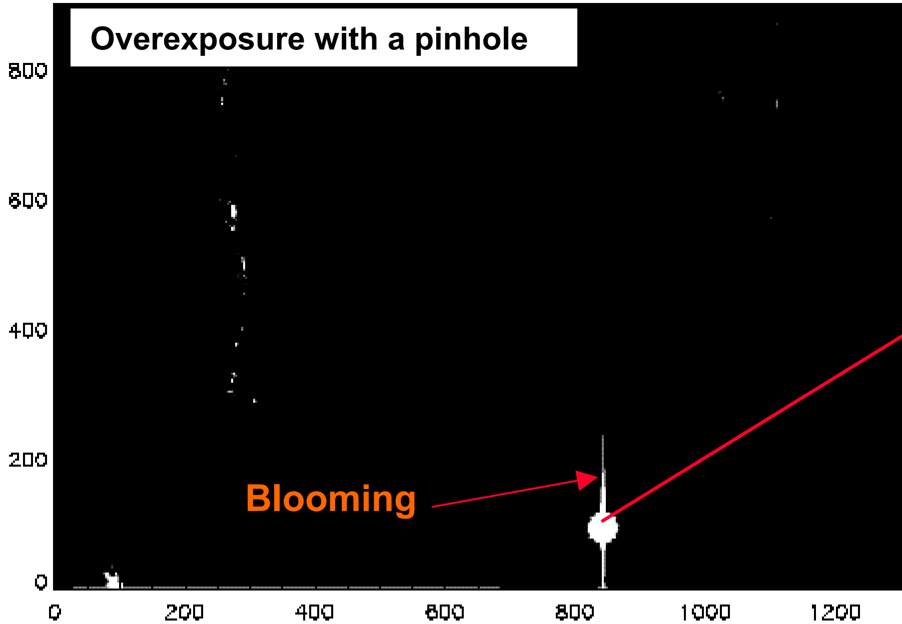
Measured Charge Capacity for
1100x800 CCD with 15 μm Pixels
Charge per Pixel (e-)
200000
180000
160000
140000
120000
100000
80000
60000
40000
20000
0
0
1
2
3
Exposure Time (sec)

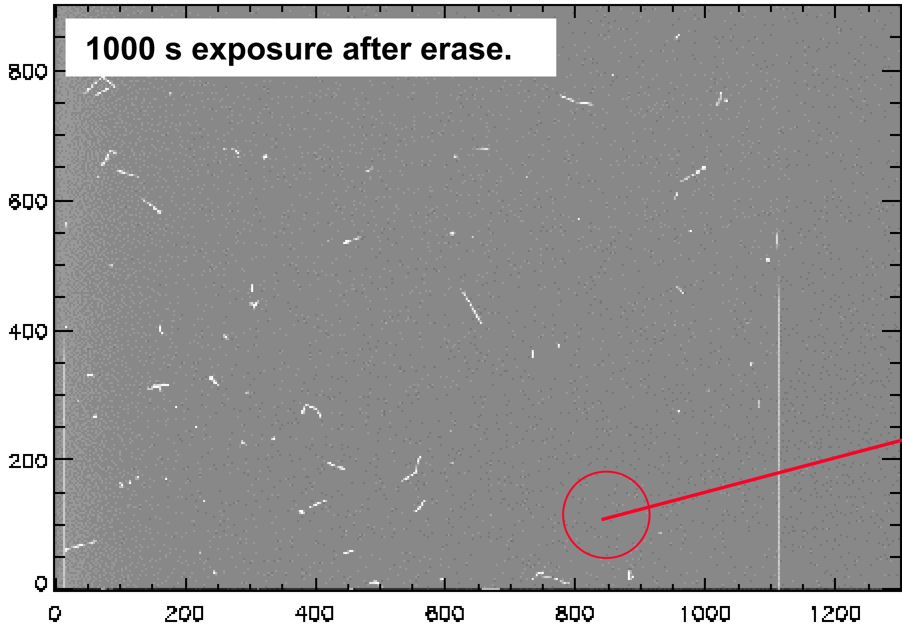
Persistent Images

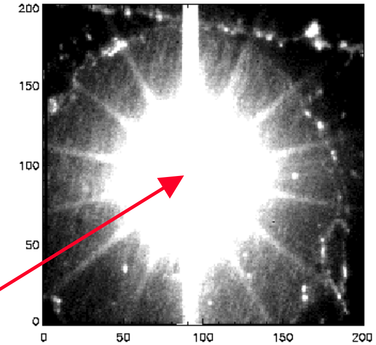
Saturated images due to trapped holes can persist for hours or even days depending on the CCD temperature.

Erase by inverting the surface with electrons from the channel stop.

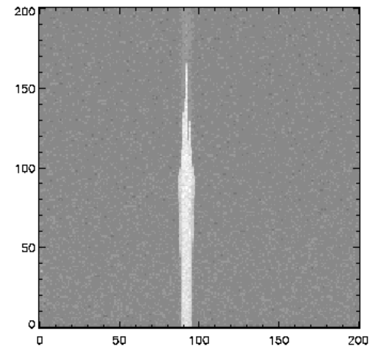
Suppress surface dark current via long time constant of trapped electrons.



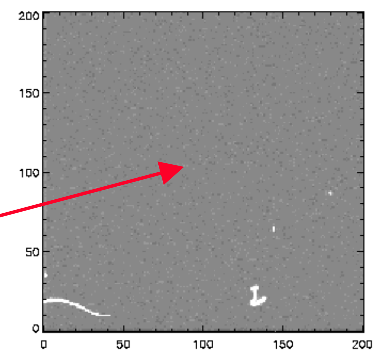




Saturating exposure



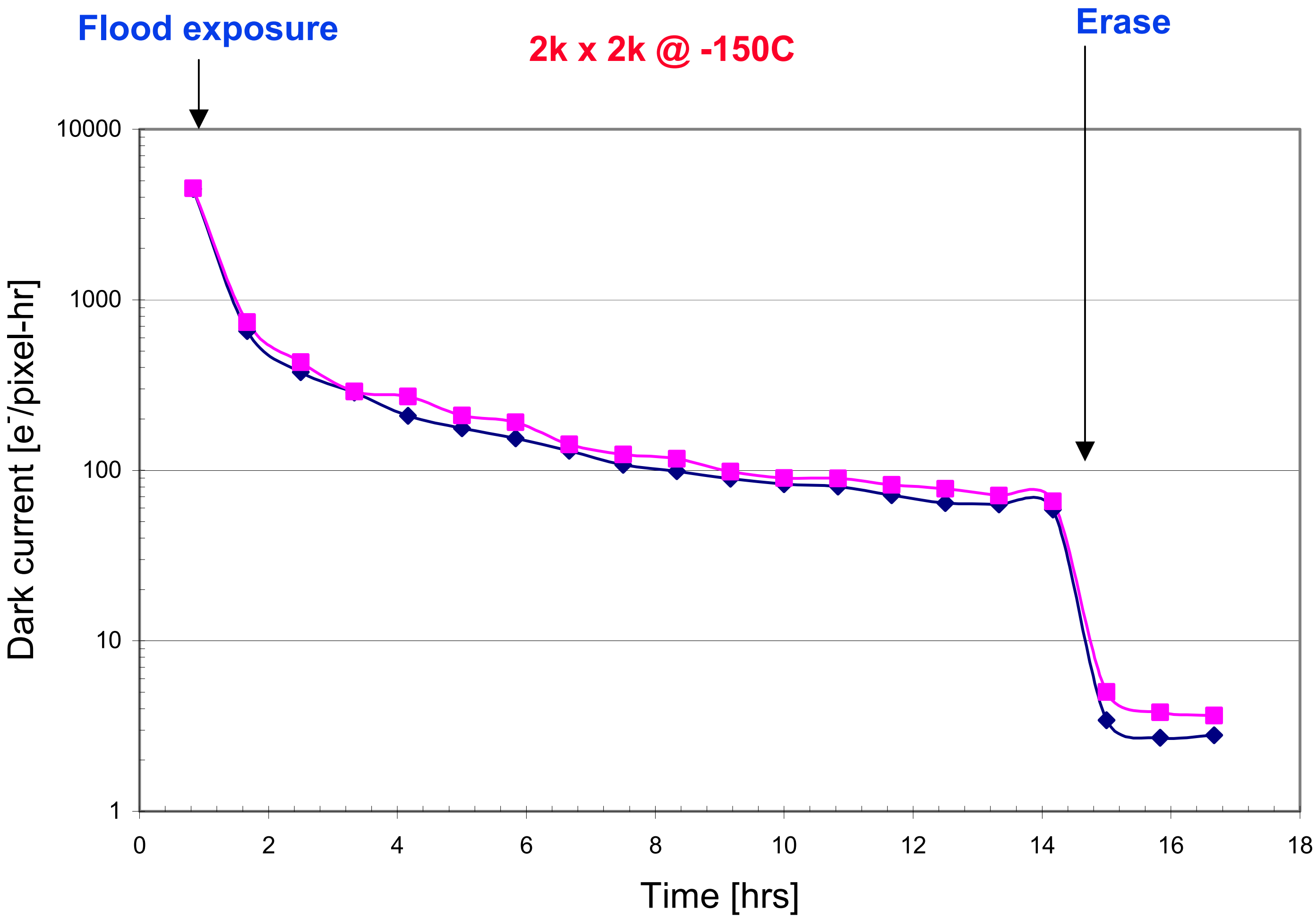
Persistent image



Erased image

1 e⁻/hr/15 µm pixel

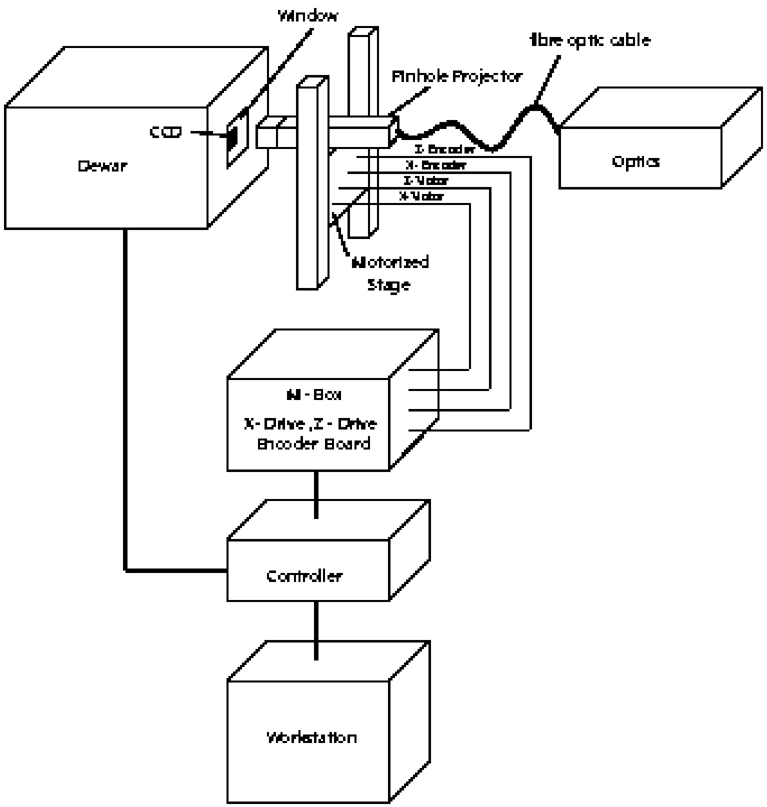
Persistent image erase

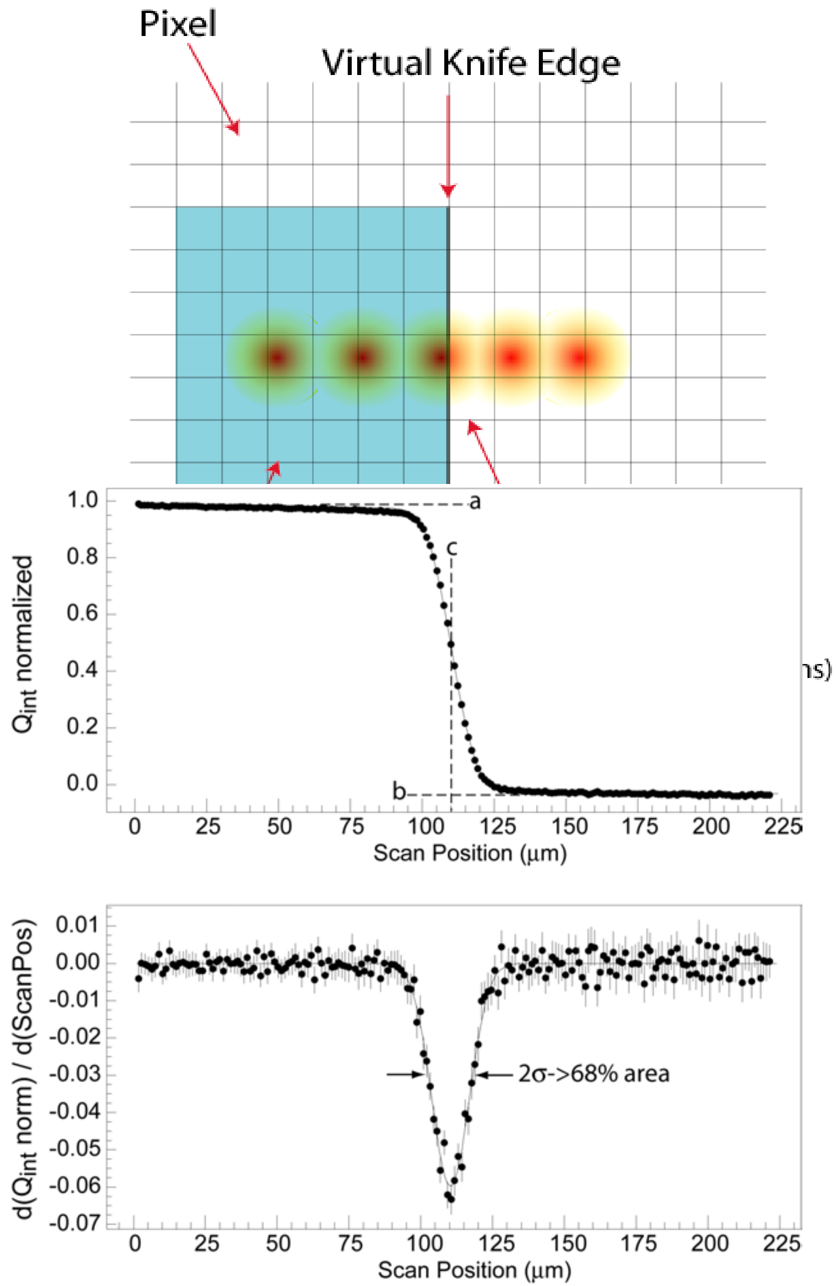


PSF / MTF / Diffusion

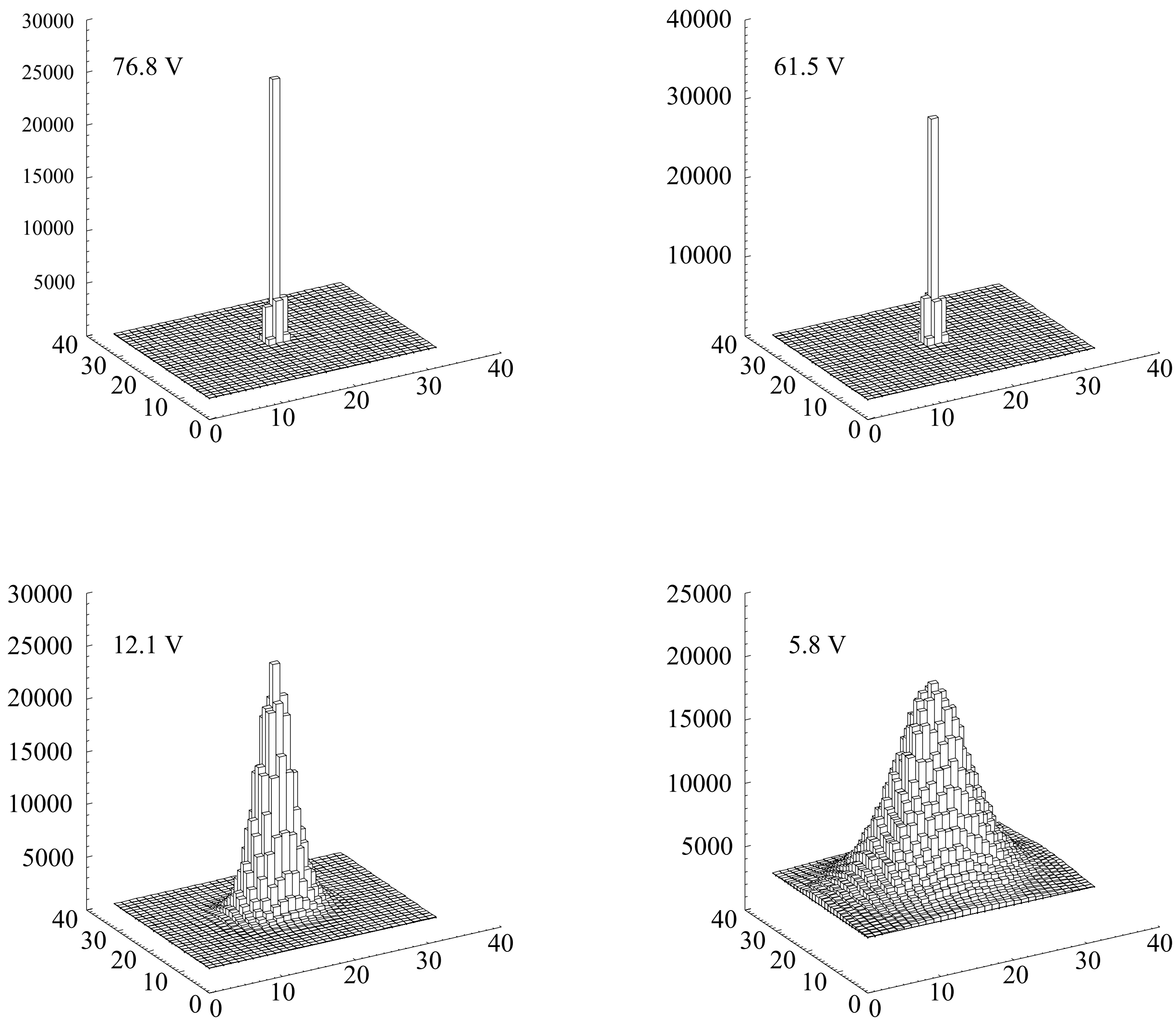
Study of Diffusion in LBNL CCDs

LBNL pinhole projector
Beam spot size 1.3 µm rms
Step size 0.4 µm with 0.1 µm resolution



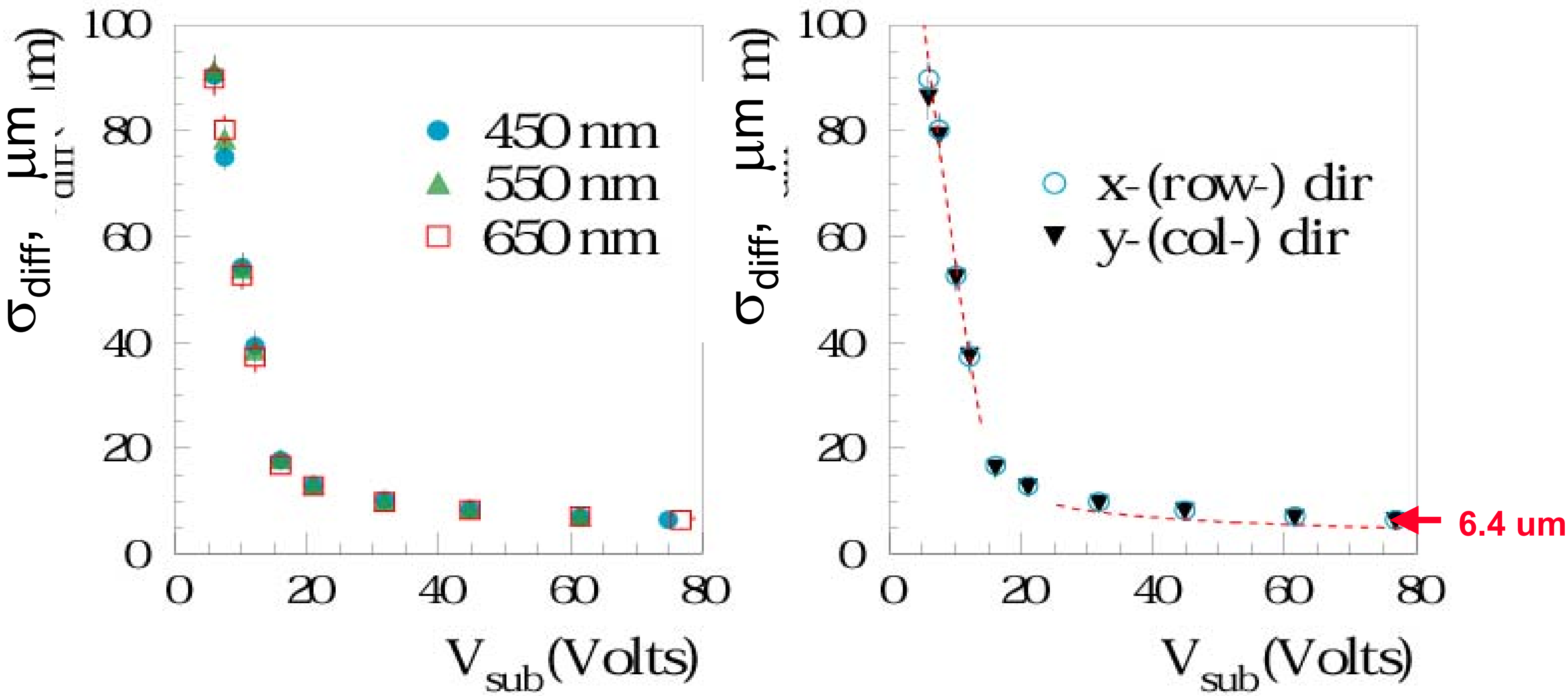


"Dial in" PSF with bias voltage



x-y axis: pixel number z axis; arbitrary units
1100 x 800 back-illuminated CCD, 15 μm pixels

PSF Measurement



Note that 6.4 um in a 280 um thick device should scale to ~4 um in a 200 um thick device

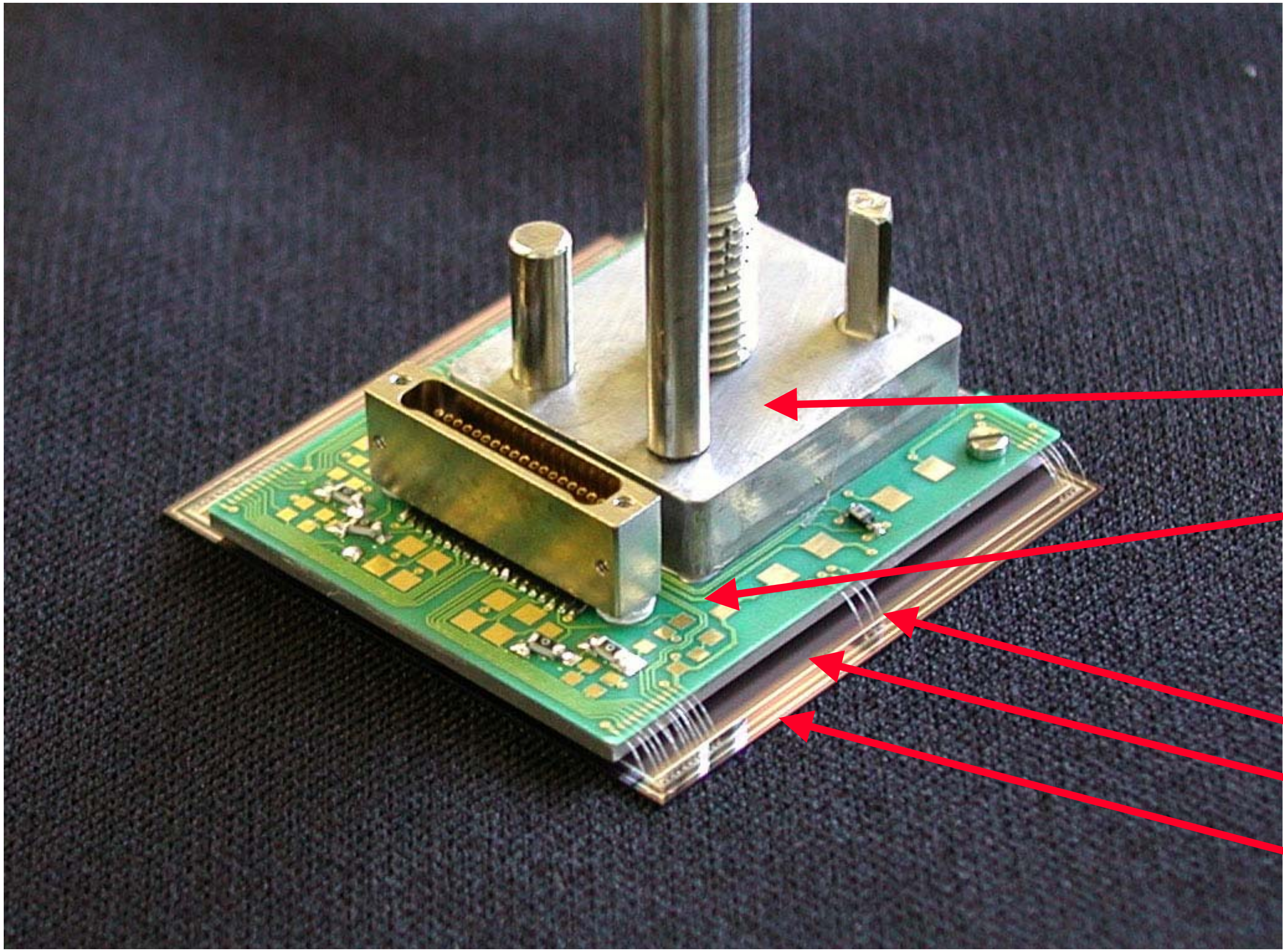
"*Measurement of Lateral Charge Diffusion in Thick, Fully Depleted, Back-illulminated CCDs,*"
by C.J. Bebek, A. Karcher, W.F.Kolbe,D.Maurath,V.Prasad,M.Uslenghi,M.Wager
Presented by A. Karcher at 2003 IEEE meeting

Packaging

CCD Packaging R&D

- **Packaging effort is in support of CCD development effort**
- **Have developed several types of packaging**
  - — **simple window frame mount to support device characterization**
  - — **4-side abuttable, *wire-bonded* mount for ground-based astronomy**
    - One LBNL-packaged device is a candidate for the KECK ESI
    - Two more devices requested for KECK LRIS spectrograph upgrade (will be packaged by Richard Stover at UC Lick Observatory)
  - — **3-side abuttable, *bump-bonded* mount for ground-based astronomy**
    - Improve by completely supporting CCD, eliminating wirebonds
  - — **4-side abuttable, *bump-bonded* mount for SNAP**
    - Goal: mount large-format CCDs in 4-side abuttable package
    - Yale is beginning to fabricate mechanical prototypes
    - Want to be ready to package first SNAP v. 1 CCDs from the current fabrication run

4-side abuttable, wirebonded packaging prototype



Moly foot with mounting pins

Circuit board and connector

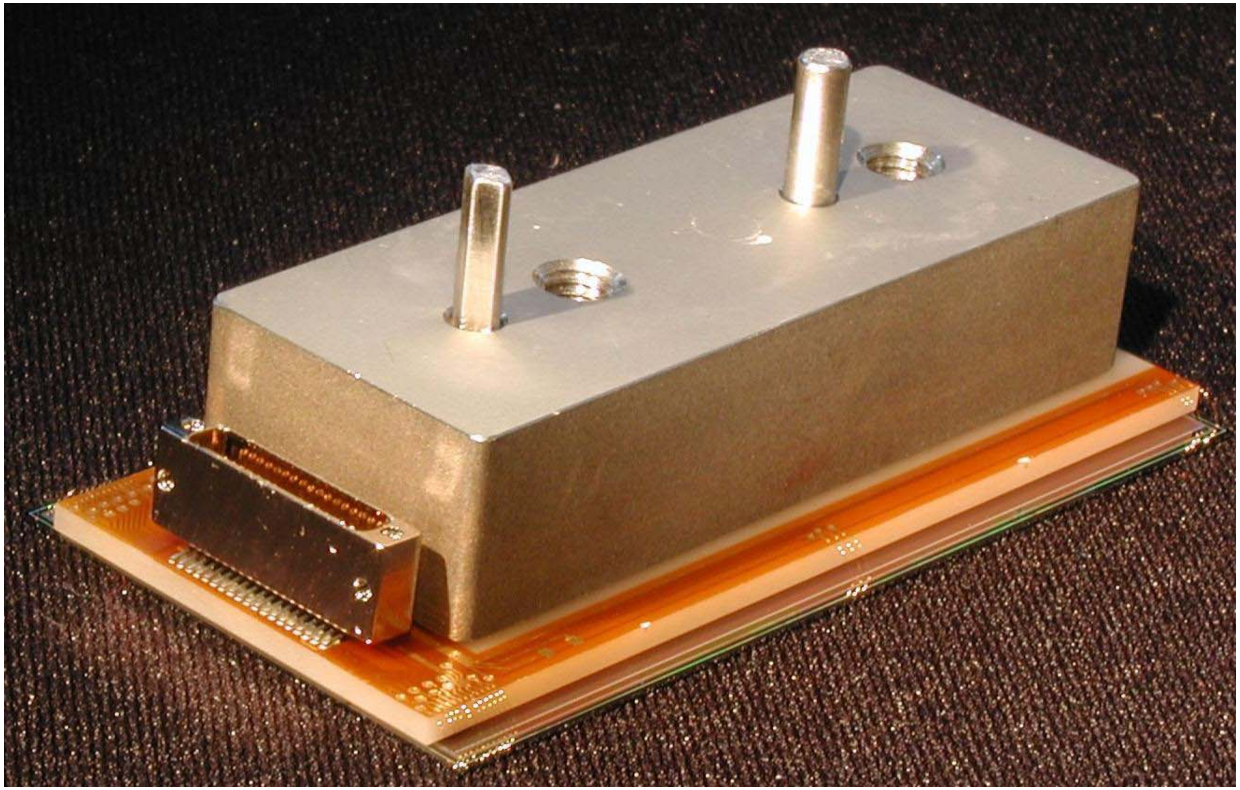
Wirebonds

AlN substrate

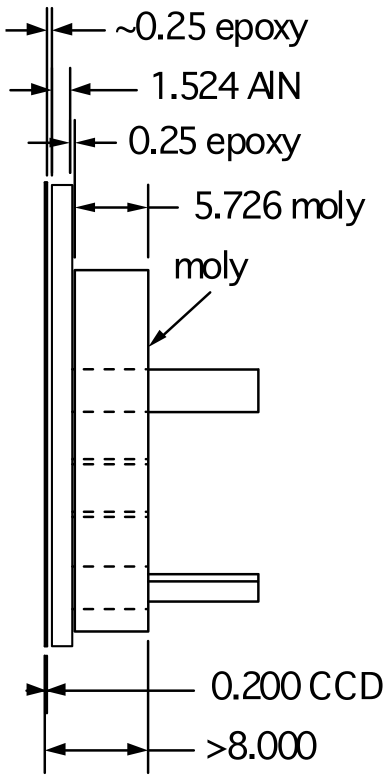
CCD on bottom

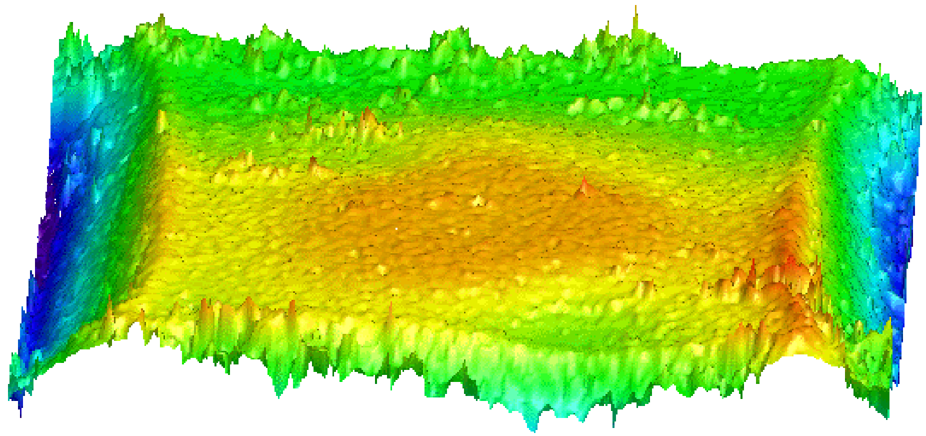
LBNL packaged 4k x 2k (15 μm) CCD

- Performance results at –140C (SPIE 5167, August 2003):
  - — Noise 4.5 e- rms
  - — Dark current 7 e-/pix-hr
  - — CTE > 0.999995 parallel and serial
  - — Linearity Better than 1%
  - — Well depth 160,000 e-



Flatness

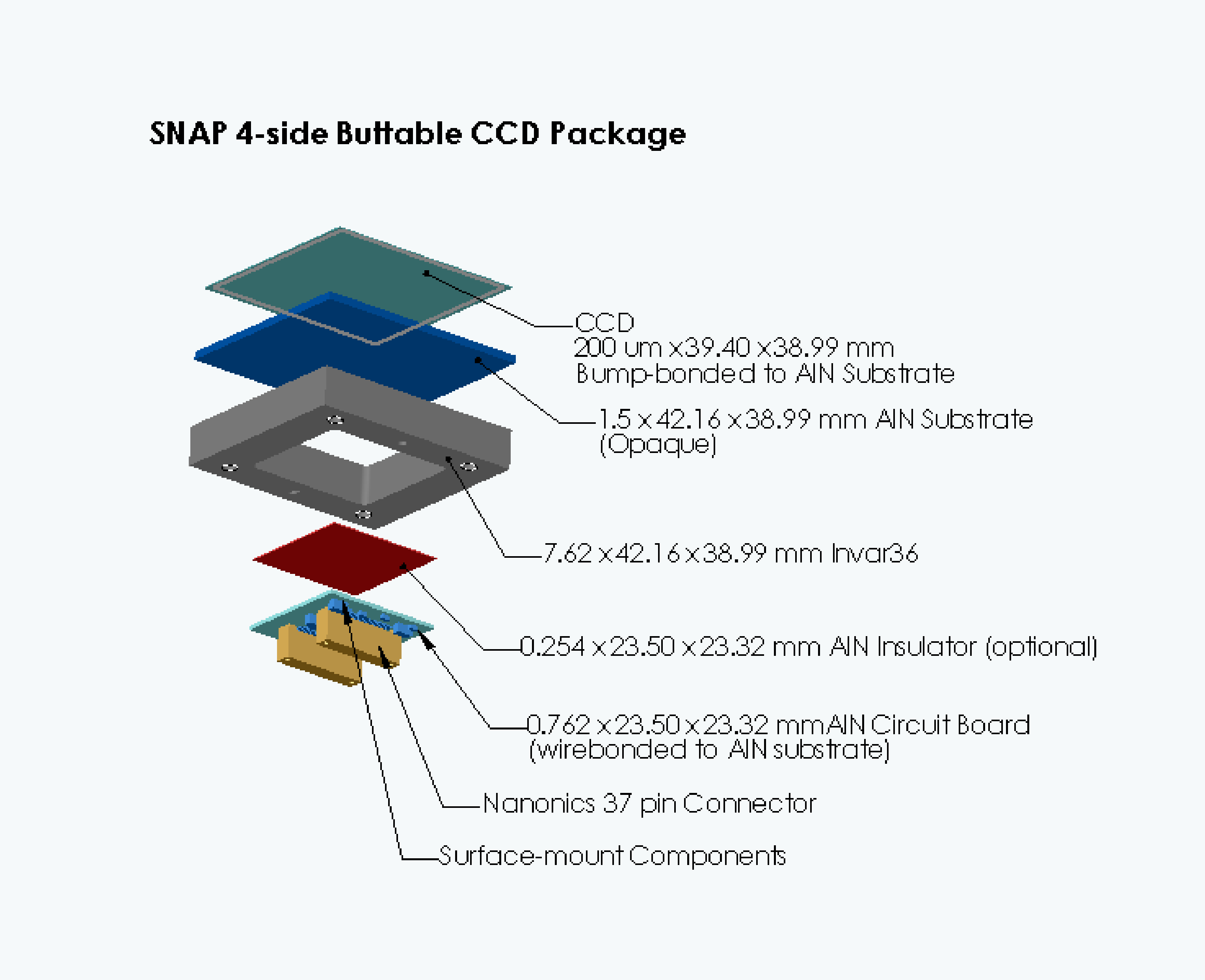




Speckle interferogram of CCD surface – excursions less than 10 um.

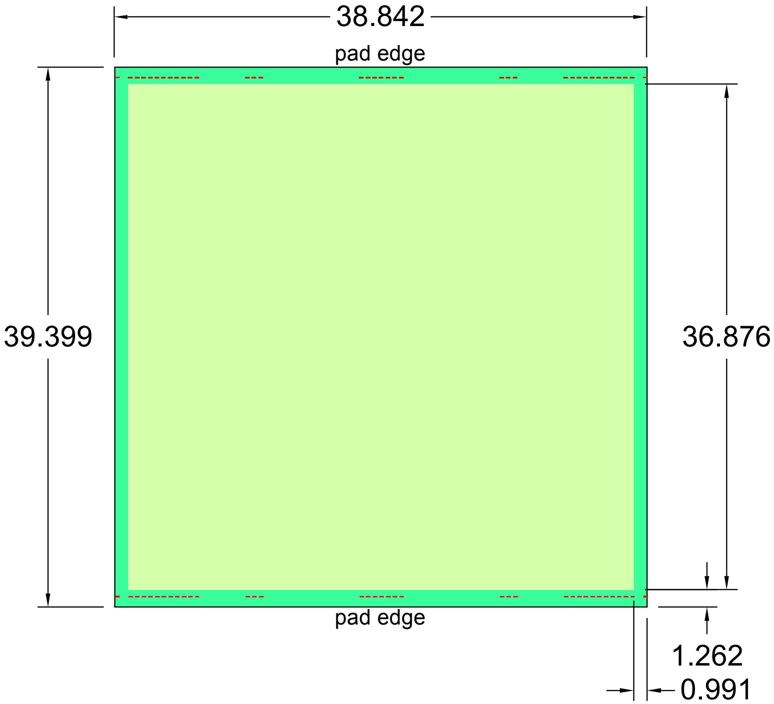
Preliminary results at UCO/Lick using a porous ceramic vacuum chuck during glue cure time had 2 um surface flatness.

4-side abuttable, bump-bonded SNAP packaging concept

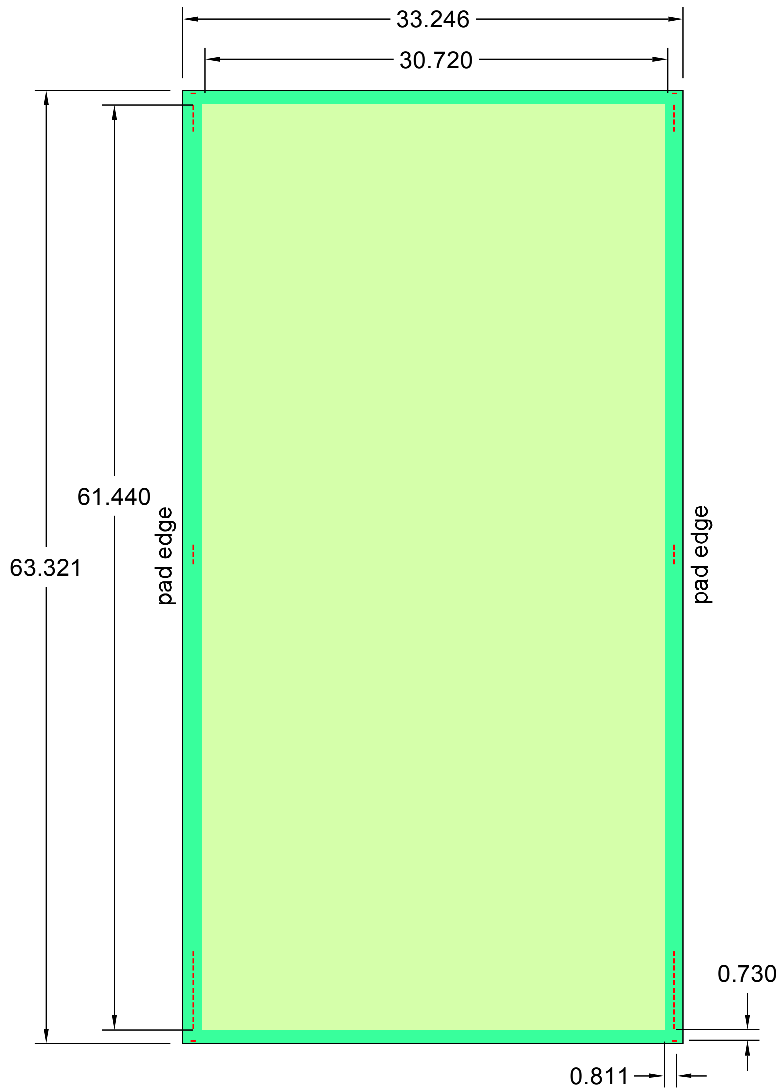


Fill factor

CCD pixel area
3512 x 3512 10.5 μm



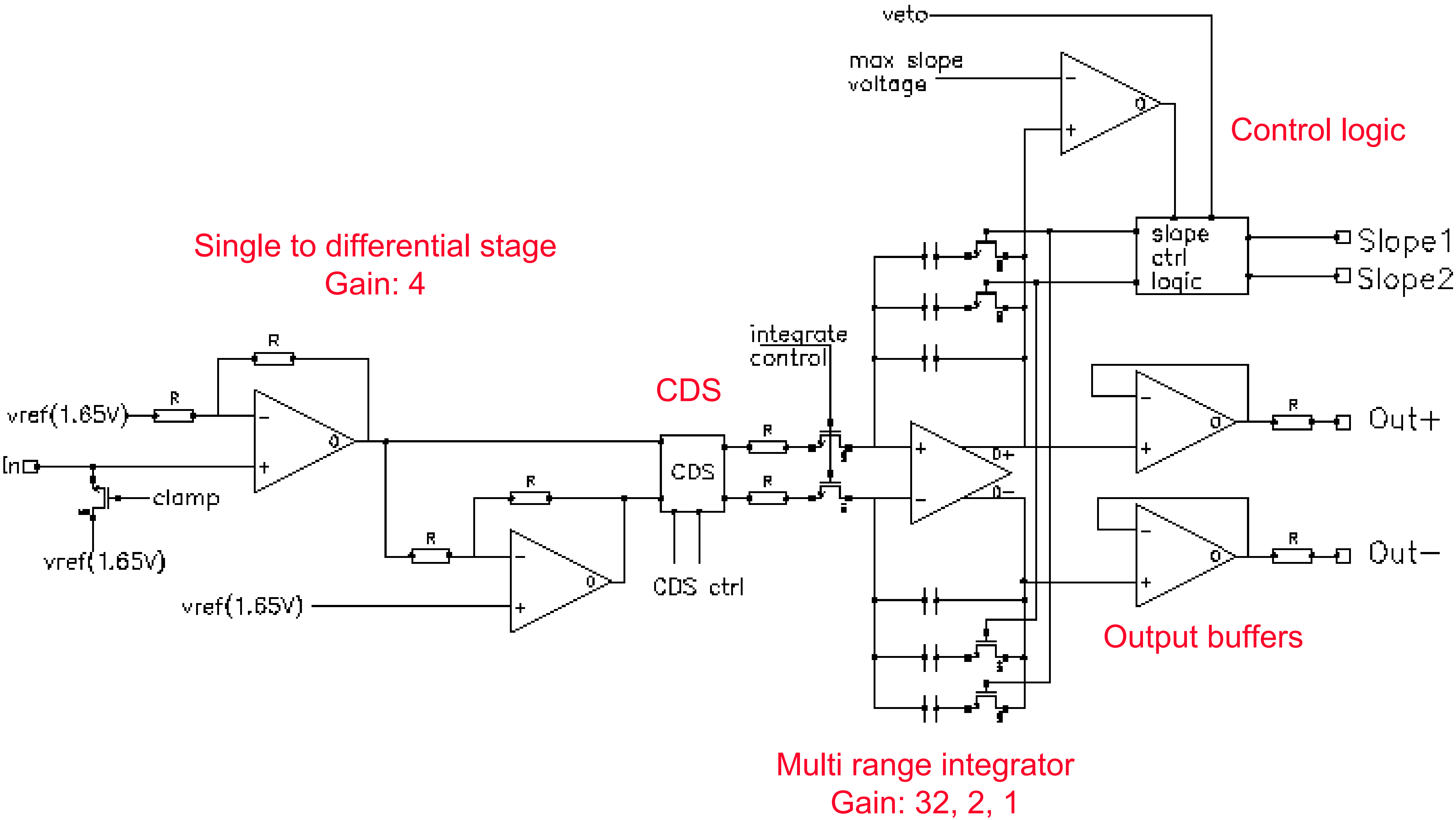
CCD pixel area
2048 x 4096 15 μm



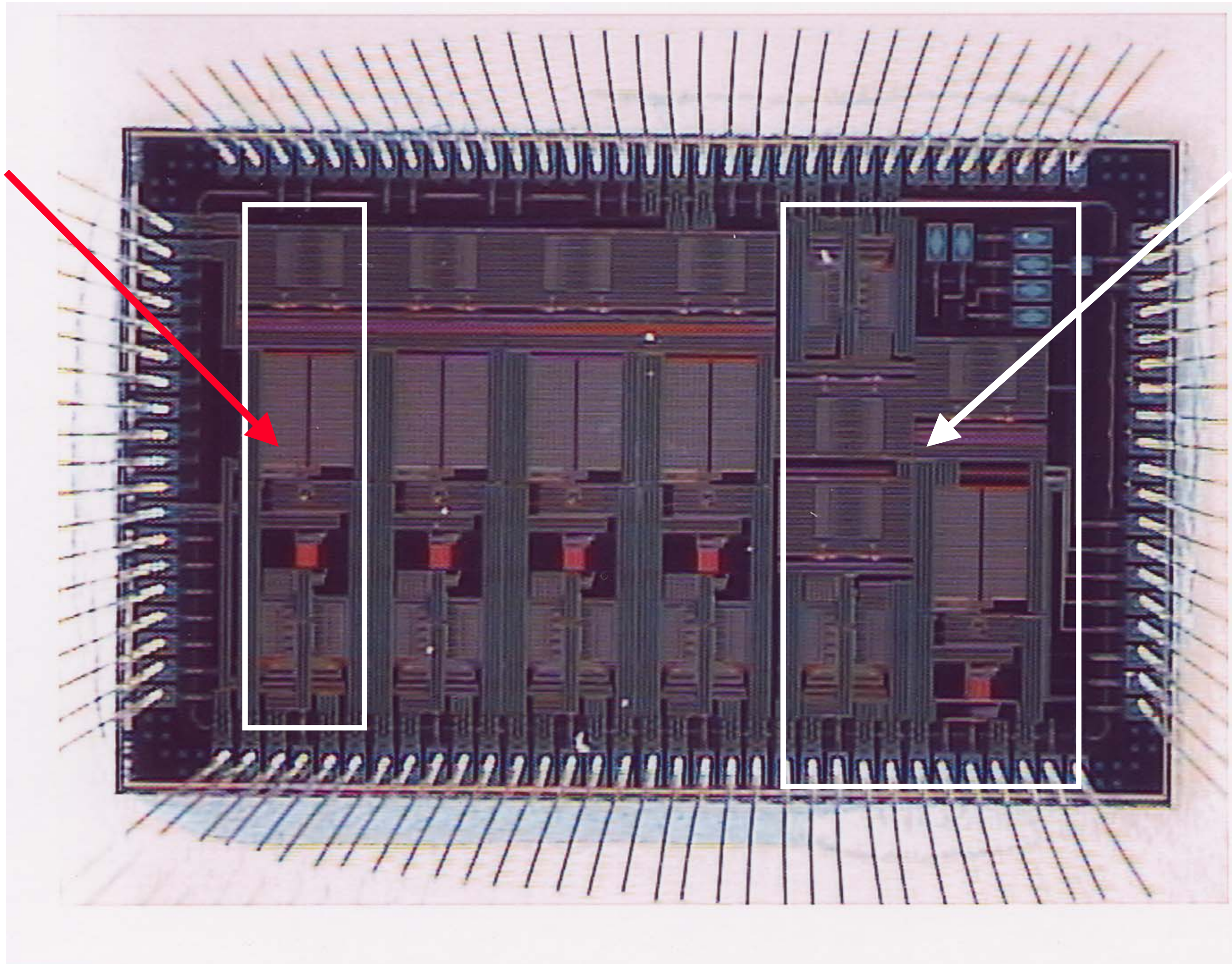
Today's die f.f.'s
SNAP: 88.9%
2kx4k: 89.7%

CRIC

Channel architecture

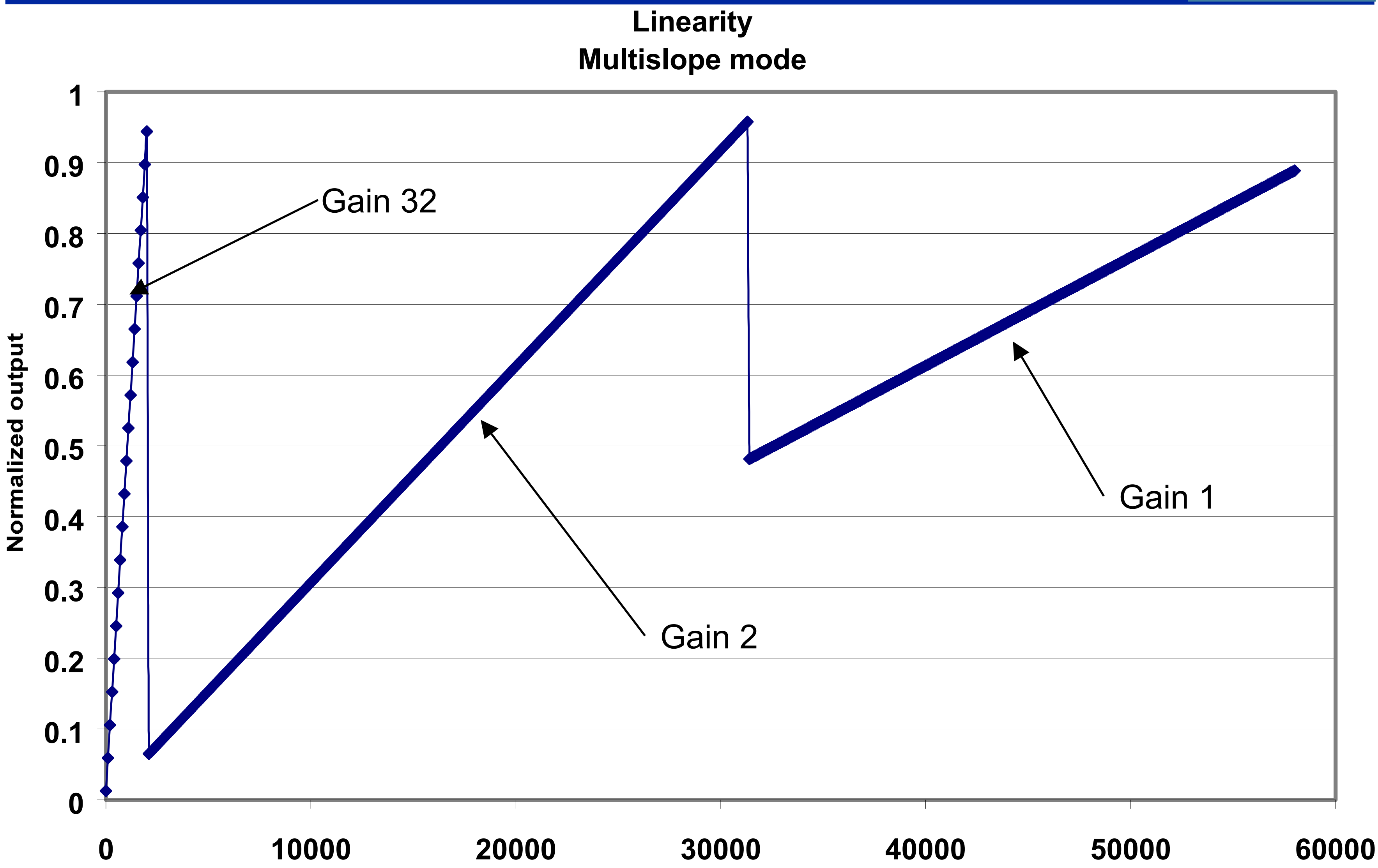


Chip photo



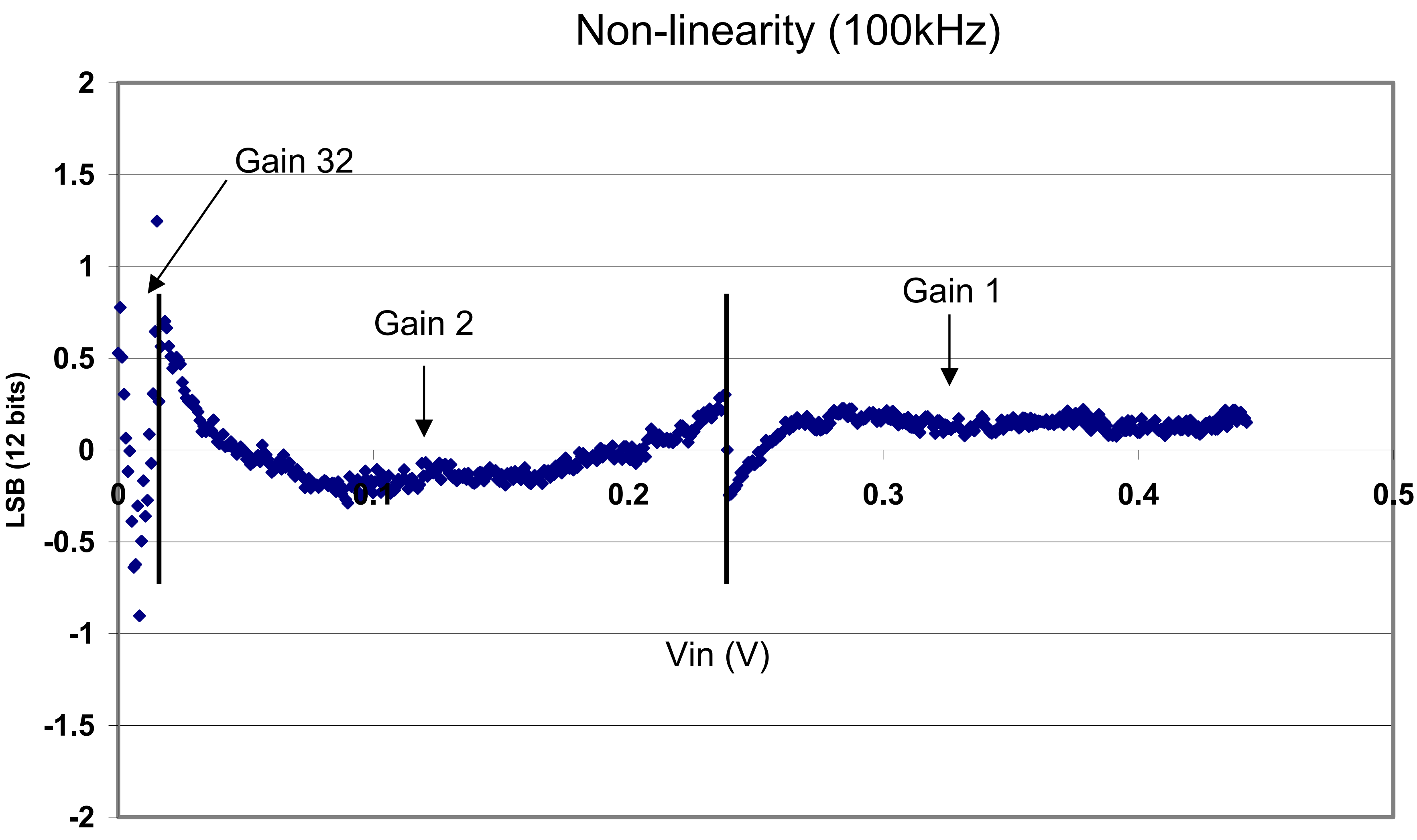
Commercial Mix Mode 0.25μm process
Die size: 3.6mm X 5.4mm.

Linearity measurement (100kHz)



1 DAC count = 14μV = 2e

Measured deviation from best fit

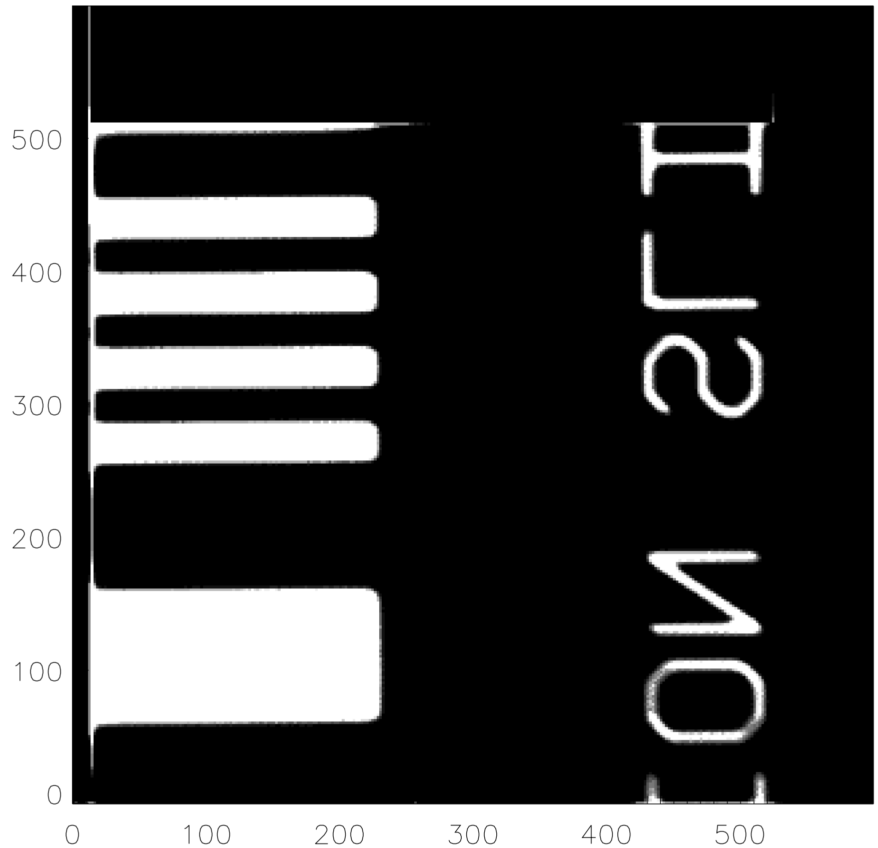


Chip Properties

- A low power, 16-bit dynamic range multi range signal processor has been integrated for the SNAP CCD readout and successfully tested.
- Tests summary:
  - Noise:
    - 300K — 2.0e- @ 100kHz, 1.5e- @ 50kHz
    - 140K — 1.6e- @ 100kHz, 1.33e- @ 50kHz
  - Linearity — 12-bit for all ranges
  - Gain(T) — 400ppm/K
  - Dynamic range — 16-bit
  - Readout speed — 100kHz & 50kHz
  - Power — 6.5mW/channel

Status

- **CCD-CRIC test**
  - — **The CRIC chip has been tested together with a 512X512 LBNL CCD**
    - **Works great!**



CRIC with ADC

- Target submission date March 29

- Main modules on the chip
  - Input amplifier
  - CDS
  - Integrator
  - 13 bit ADC with internal calibration option
  - Band-gap reference for generation of 1.65V reference voltage for the analog front-end
  - Level-shifter for generation of two additional reference voltages for the ADC
  - MCT channel with ADC

Conclusion

- **For D.E.C.:**
  - —4k x 2k 15 μm pixel devices with slow readout are in the bag.
    - Advantages for D.E.C.:
      - —I & Z-band response
      - —improved PSF
      - —photometry
  - —CRIC w/ ADC provides low-power solution
  - —Packaging is a big deal
  - —Could provide mass production of fully processed AR coated diced wafers to FNAL for packaging & test